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THE UNIVERSITY OF ALBERTA

THE GAS PHASE RACEMIZATION OF *trans*-2,3-DIVINYLOXIRANE

by

© VESNA VUKOV

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

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ABSTRACT

Optically active *trans*-2,3-divinyloxirane was prepared and the kinetics of its racemization has been studied. The comparison of the rate for racemization and the rate for the geometrical (*cis*-to-*trans*) isomerization, indicates that the former is more than 99% an electrocyclic process.

During the racemization of *trans*-2,3-divinyloxirane the formation of an optically active 2-vinyl-2,3-dihydrofuran has been observed. The study of their absolute configurations was carried out, by relating both compounds to R-(−)-3-hexanol, and showed that this 1,3-sigmatropic shift takes place with the inversion of configuration at the migrating centre. The process was classified as a ${}_{\sigma}2_{a} + {}_{\pi}2_{s}$ electrocyclic reaction.

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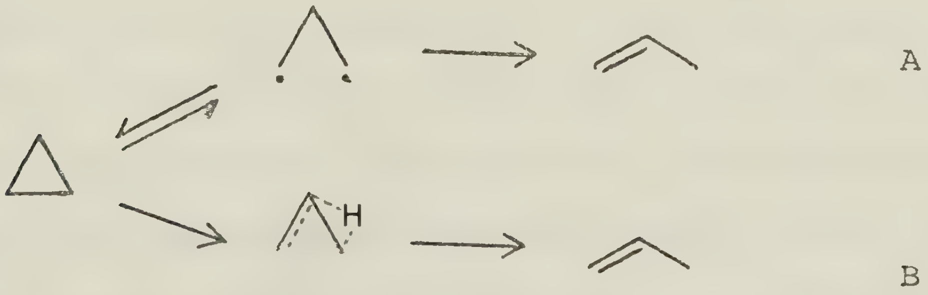
HISTORICAL

A. Thermal isomerization of cyclopropane.

A great deal of work has been done on the thermal isomerization of cyclopropane (1) to obtain more information about the nature of the carbon-carbon bond cleavage reaction. It has been observed that this rearrangement follows first-order kinetics and proceeds at a lower temperature than alkane pyrolysis. This indicates that the relief of strain helps the reaction.

First quantitative study of cyclopropane-propylene isomerization in the temperature range of 469 - 519°, was carried out by Chambers and Kistiakowsky (2). They found that this rearrangement was a homogenous unimolecular reaction with an activation energy of 65 kcal/mol and a frequency factor of $10^{15.17}$, at the high pressure limit.

They suggested two possible mechanisms:



Mechanism A involves an initial carbon-carbon bond cleavage to give a trimethylene diradical as an intermediate, which might either reclose to cyclopropane or undergo hydro-

gen migration to yield propylene.

Mechanism B postulates that bond breaking and hydrogen shift occur simultaneously.

In order to define the mechanism more precisely Rabinovitch and co-workers (3a) studied the thermal isomerization of *trans*-1,2-dideuteriocyclopropane. They found that the geometrical *cis*-*trans* isomerization was 12 times faster than structural isomerization to propylene. No deuterium scrambling was observed. The frequency factor was found to be $10^{16.4}$, suggesting the formation of an intermediate capable of undergoing free rotation and reformation of starting material (mechanism A). Rabinovitch (3) preferred the term "expanded ring" over trimethylene diradical for this intermediate, since it was shown that it cannot be trapped by scavengers like oxygen (3b), nitric oxide (4a) or ethylene (4b). This implies that the two electrons involved retain some interaction.

Benson (5a) has carried out a transition-state theory calculation on mechanism A, and concluded that the ring-opening can occur without hydrogen shift, so that the rate determining step for olefin formation involves migration of hydrogen in an initially formed short-lived diradical (10^{-11} sec). Using the same mechanistic scheme for the addition of methylene to ethylene (5b), he correctly predicted the propylene to cyclopropane ratio. He suggested the following reaction coordinate:

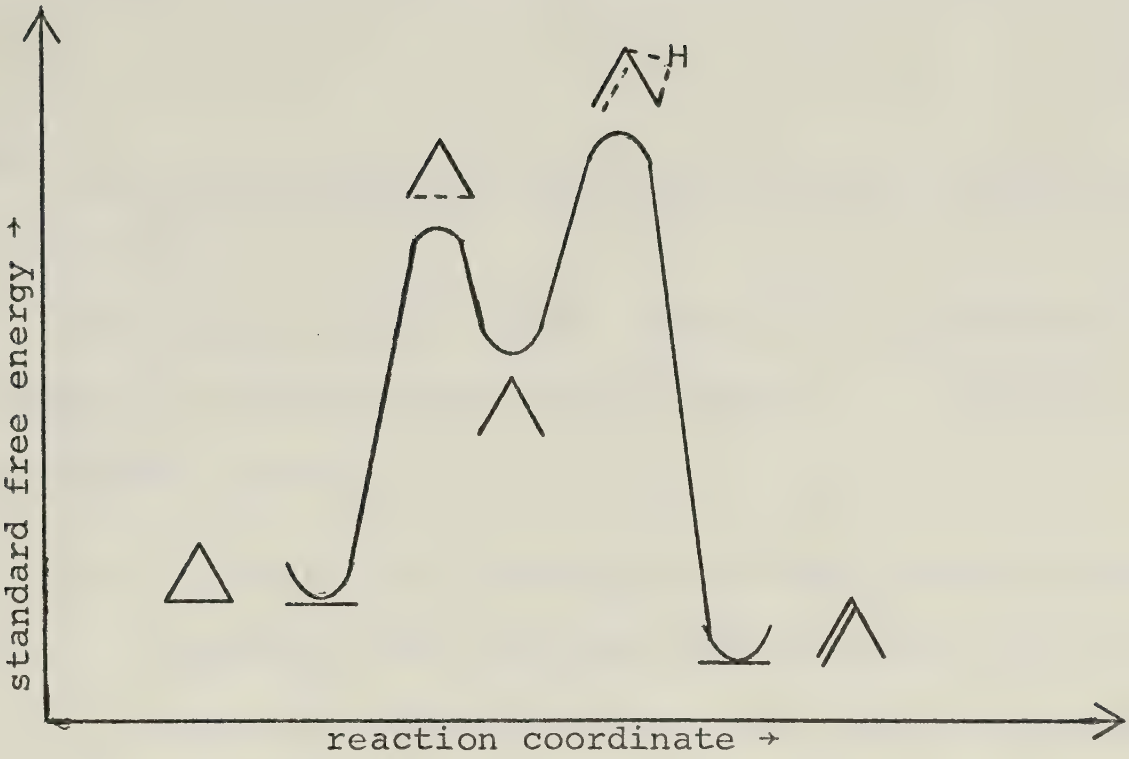
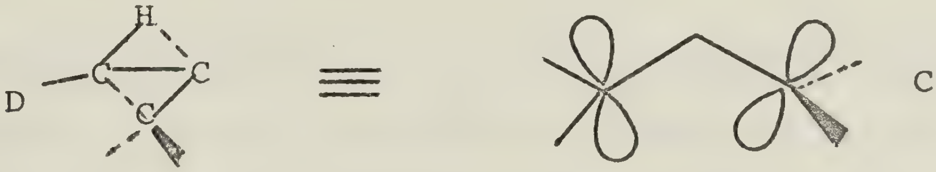


FIGURE 1. Plot of Standard Free Energy *versus* Reaction Coordinate.

An alternate mechanism, was proposed by Smith (6), involving the transition state C.



All five atoms shown were assumed to be coplanar and the hydrogen atom to be partially bonded to the adjacent carbon atom, a process which requires the twisting of the D-C-H group. When the molecule returns to its initial state, isomerization has occurred without deuterium scrambling.

Benson (5c) criticized this model on an energetic ground, suggesting that the activation energy for $-CH_2-$ twist would be much greater than the observed energy of about 60 kcal/mol. Secondly he pointed out that the frequency factor for such a transition state could not be higher than

10^{15}, which is an order of magnitude too low, compared with the observed.

One cannot however simply discard this mechanism, since a number of arguments can be put forward in favor of such a transition state:

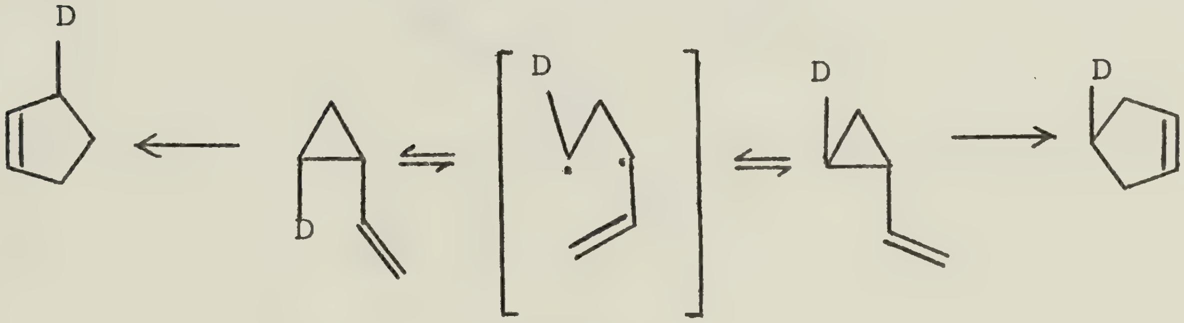
(a) It follows the principle of least motion, according to which those reactions that involve the least change in atomic positions and electronic configurations are favored (7).

(b) It releases the eclipsing effect of the groups in the substituted cyclopropane.

B. Thermal isomerization of vinyl-substituted cyclopropanes.

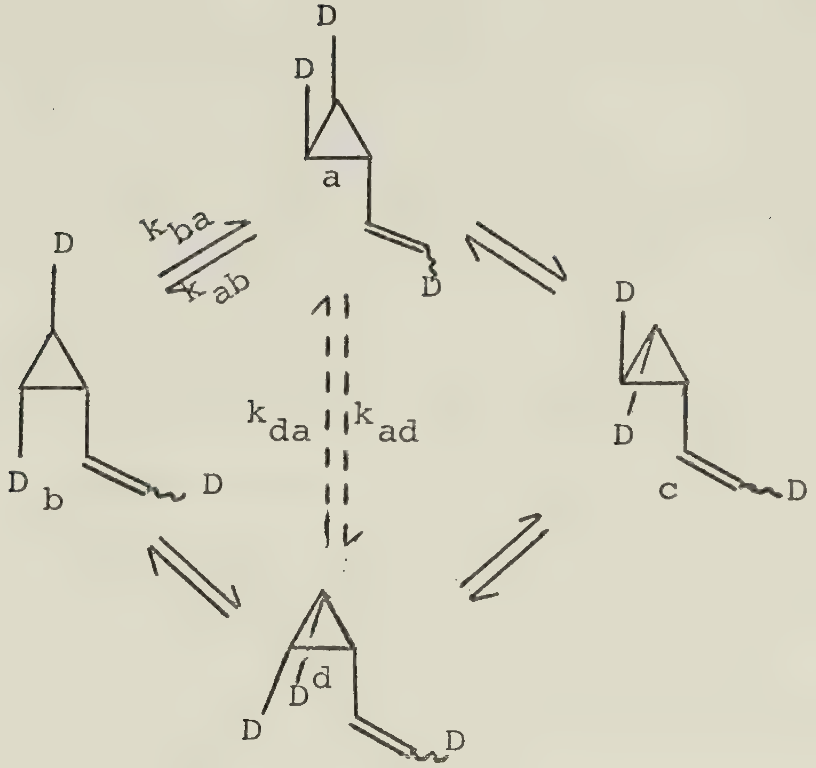
Another type of cyclopropane isomerization was observed when vinylcyclopropane was heated above 300° (8). It yielded mainly cyclopentene with small amounts of 1,4-pentadiene and *cis* and *trans*-1,3-pentadiene. Five member ring-closure proceeds with an activation energy of 49.7 kcal mol^{-1} and a frequency factor of $10^{13.6}$, both parameters being significantly lower than those observed for the isomerization of cyclopropane. These results were interpreted on one hand in terms of a trimethylene diradical (9a,b) and on the other hand as a concerted rearrangement (10). Willcott and Cargle (11) investigated thermal isomerization of 1-vinyl-cyclopropane-2-d, at 360°. They found that after 6% of cyclopentene was

formed, complete deuterium *cis-trans* isomerization had occurred, in the starting material. They concluded that the loss of stereospecificity at the deuterium labelled site is at least five times faster than the conversion to cyclopentene. These results support the intervention of a diradical species as an intermediate for the geometrical isomerization.



A decrease in activation energy of 13 kcal/mole is then easily understood in terms of the allylic resonance stabilization of the intermediate (9b).

The same authors (12) investigated the thermal geometrical isomerization of *cis*-2,3-dideuteriovinylcyclopropane in order to make a distinction among the three limiting sets of molecular motion, as shown on Scheme 1.



SCHEME 1

(I) A simultaneous epimerization at two of the three carbon atoms in the ring (when k_{ad} is much faster than k_{ab}).

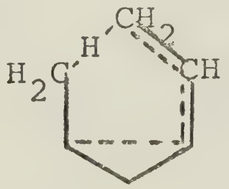
(II) An epimerization exclusively at one carbon atom (when k_{ad} is nonexistent).

(III) Randomization of the stereochemistry at two of the three carbon atoms in the ring (when $k_{ab} = k_{ad}$).

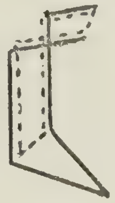
Experimental results were consistent with the case III, thus rendering evidence for the intervention of the diradical, wherein the stereochemistry at two of the carbons is randomized during each isomerization process.

A number of other alkyl substituted vinyl-cyclopropanes have been studied and the activation parameters for a few examples are shown in Table I.

On the basis of the much lower temperature required and the clean rearrangement to a single product with the *cis* isomers, a concerted transition state has been postulated, i.e. a concerted 1,4-hydrogen shift for 1-methyl-2-vinylcyclopropane (1) and concerted "Cope type" rearrangement for *cis*-1,2-divinylcyclopropane (2a).



1

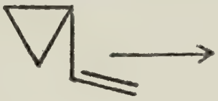
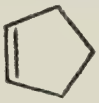
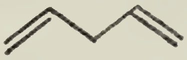
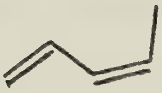
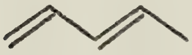
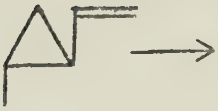
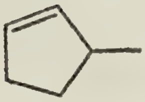
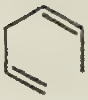
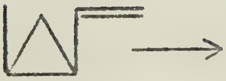
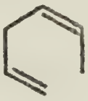
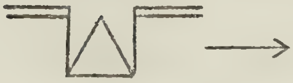
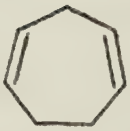
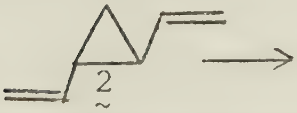
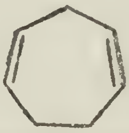


2a

Such a transition state would be difficult to achieve in the case of the *trans* isomers. It has been suggested that those rearrangements involve breaking of the carbon-carbon bond to give a diradical, which can then rotate and reclose to the *cis* isomer. An anomalous fact in the thermal isomerization of *trans*-1,2-divinylcyclopropane (2) is the absence of 4-vinylcyclopentene among the products,

TABLE I

Activation Parameters for the Thermal Isomerization of Vinylcyclopropanes

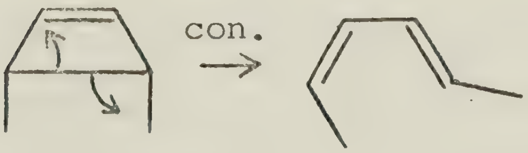
Compound	Products	Log A	E_a(kcal/mol)	Reference
		13.5	49.6	13,14
→		14.4	57.3	14
→		13.9	56.2	14
→		13.0	53.6	14
		13.67	48.7	15
→		14.74	48.7	15
 1		11.03	31.3	15
 2a			21 estimated	16
 2		12.09	32.1	17

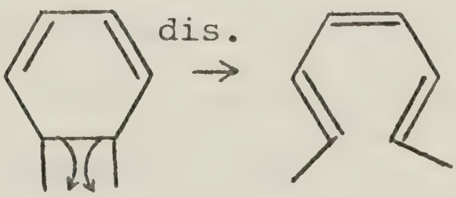
even though it is stable under the conditions of the isomerization. If a diradical is involved as an intermediate, one would expect that it would close more readily to the five-membered ring than to either a three- or seven-membered ring.

C. Optical isomerization of 1,2-disubstituted cyclopropanes.

In recent years a considerable amount of work has been done to define the nature of trimethylene diradical more precisely and some theoretical calculations have been carried out by Hoffman (18).

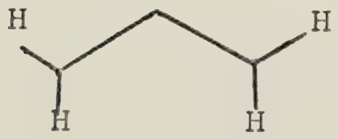
The cleavage of a carbon-carbon bond is assumed to occur by pulling two carbon atoms away from each other along a bond axis. Recent work by Woodward and Hoffman (19) suggests that in some cases this process can occur more readily by the rotation of two groups with respect to one another. Such an electrocyclic cleavage can proceed, for a thermal reaction, either in a disrotatory fashion, if there are (4n + 2)π electrons, or in a conrotatory fashion if there are 4nπ electrons in the open chain system. In other words the symmetry of the highest occupied molecular orbital dictates the mode of opening and closing.



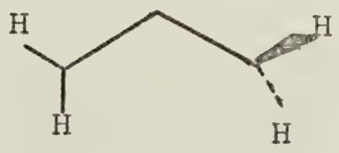


Cleavage of a carbon-carbon single bond in cyclopropane can be then considered to be the simplest case of an electrocyclic reaction, involving a two-electron system. Simple application of the above mentioned rule, would predict a disrotatory mode of ring opening and a disrotatory mode of closure of the trimethylene to cyclopropane.

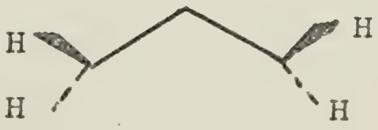
This however is an oversimplification, Hoffman (18) has carried out theoretical calculations on a trimethylene species (3) using the extended Hückel molecular orbital method. The total energy of the system was investigated in respect to three degrees of freedom of the molecule, the central CCC angle and the rotations of the terminal methylene groups in respect to a plane defined by the three carbon atoms. Three geometries are then possible for the ground state of 3.



0,0



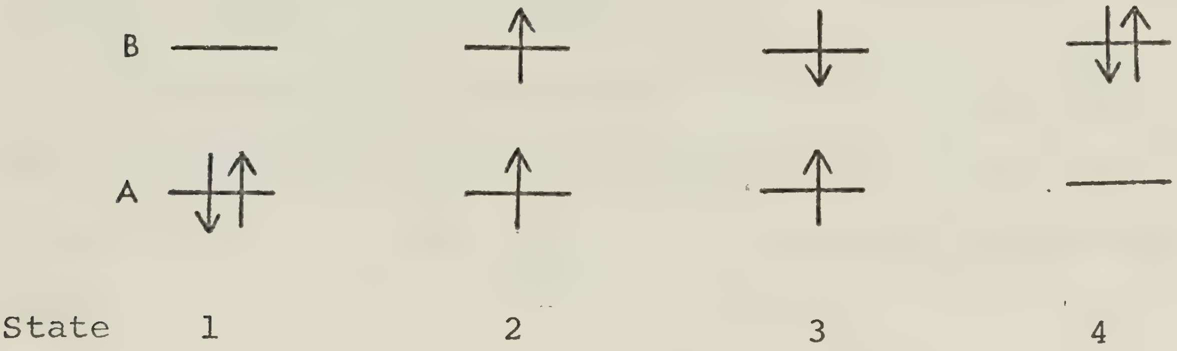
0,90



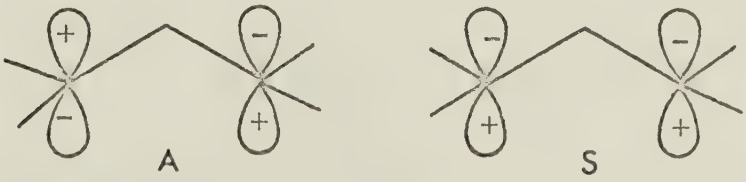
90,90

It was found that the 90,90 geometry is the most stable one at a small CCC angle, and that the 0,90 geometry- which is similar to Smith's intermediate (page 3) - would be the least stable. However, at larger CCC angles (more

than 110°) 0,0 geometry becomes stabilized over the other two. Further from the calculations it follows that the singlet trimethylene (state 1) is the ground state for this intermediate.



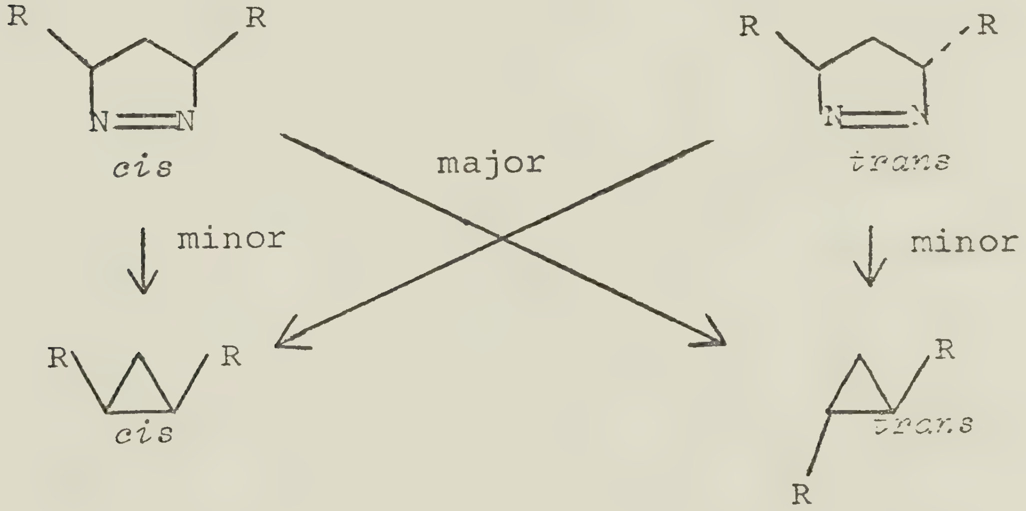
These observations led to some very striking predictions about the stereochemistry of cyclopropane ring opening and closure. When the ground state of $\underset{\sim}{3}$ was taken as state 1 with 0,0 geometry, it was found that the antisymmetric level has an energy of 0.55 ev lower than the symmetric level.



This was attributed to the mixing between C-H orbitals on C-2 into the symmetric orbitals of pseudo π system, resulting in the increase in energy of S orbital, leaving the non-interacting A orbital unaffected. Thus the predicted

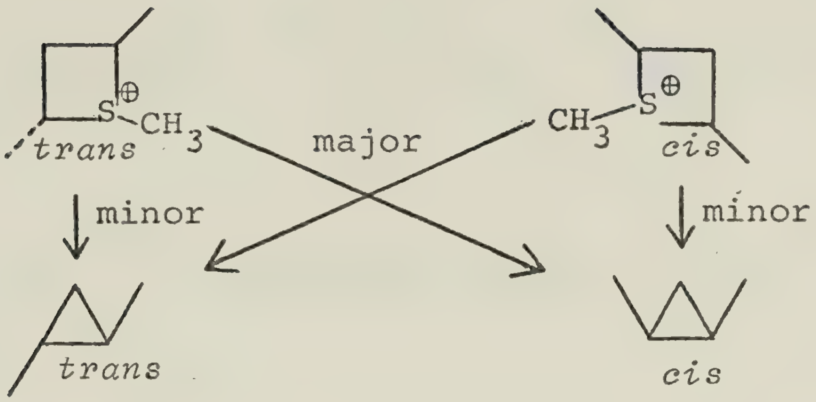
preferred motion for the two terminal methylene groups to reclose to cyclopropane is in the conrotatory fashion. This so-called "π-cyclopropane" should also have a barrier to internal rotation. On the other hand the excited configurations of 3 (state 2 and 3 on page 11) are "floppy" molecules without rotational barriers.

Preference for conrotatory closure of intermediate 3 was earlier demonstrated by Crawford and Mishra (20) in the thermolysis of *cis* and *trans*-3,5-dimethyl-1-pyrazoline, as shown in Scheme 2.



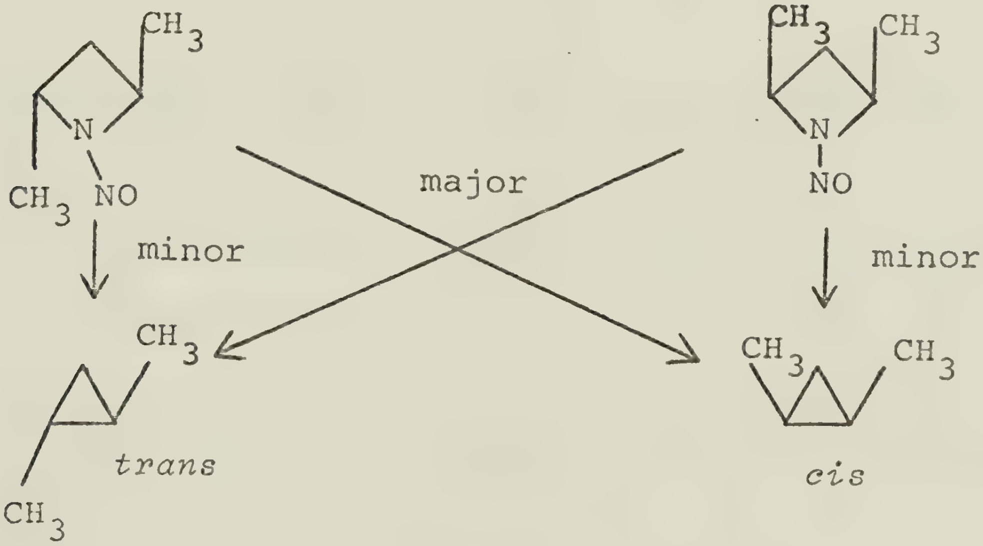
SCHEME 2

It was suggested (21) that the same type of intermediate plays a role in the fragmentation of thietanonium salts, in the presence of n-butyllithium, which proceed with the high degree of stereoselectivity (Scheme 3).



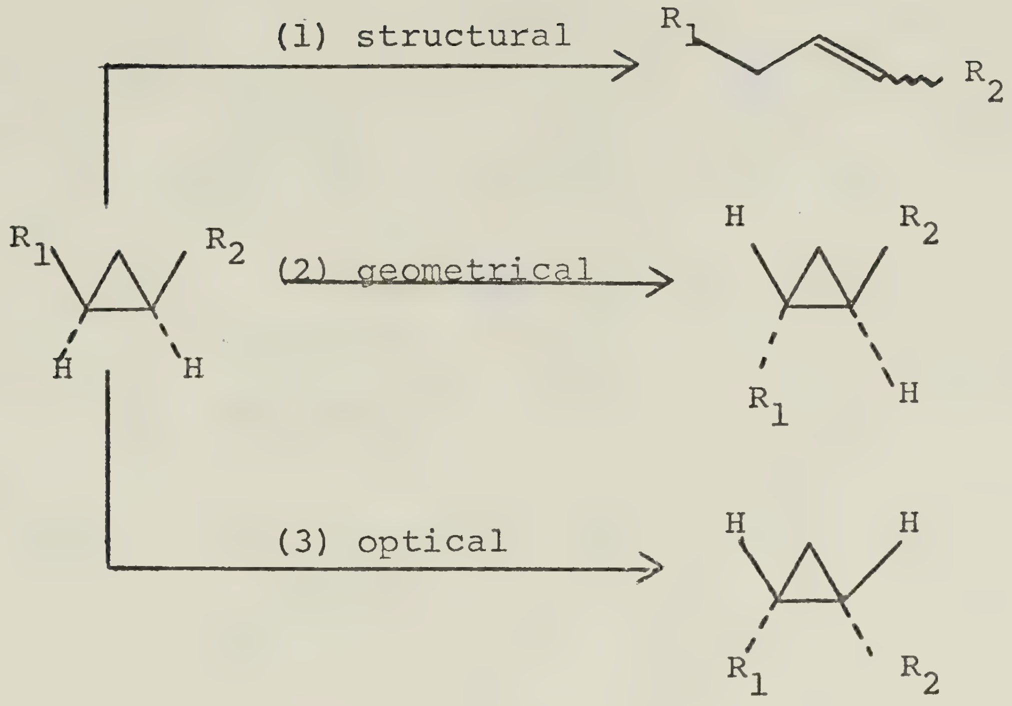
SCHEME 3

Recently (22) similar results were obtained in the deamination of azetidine (Scheme 4)



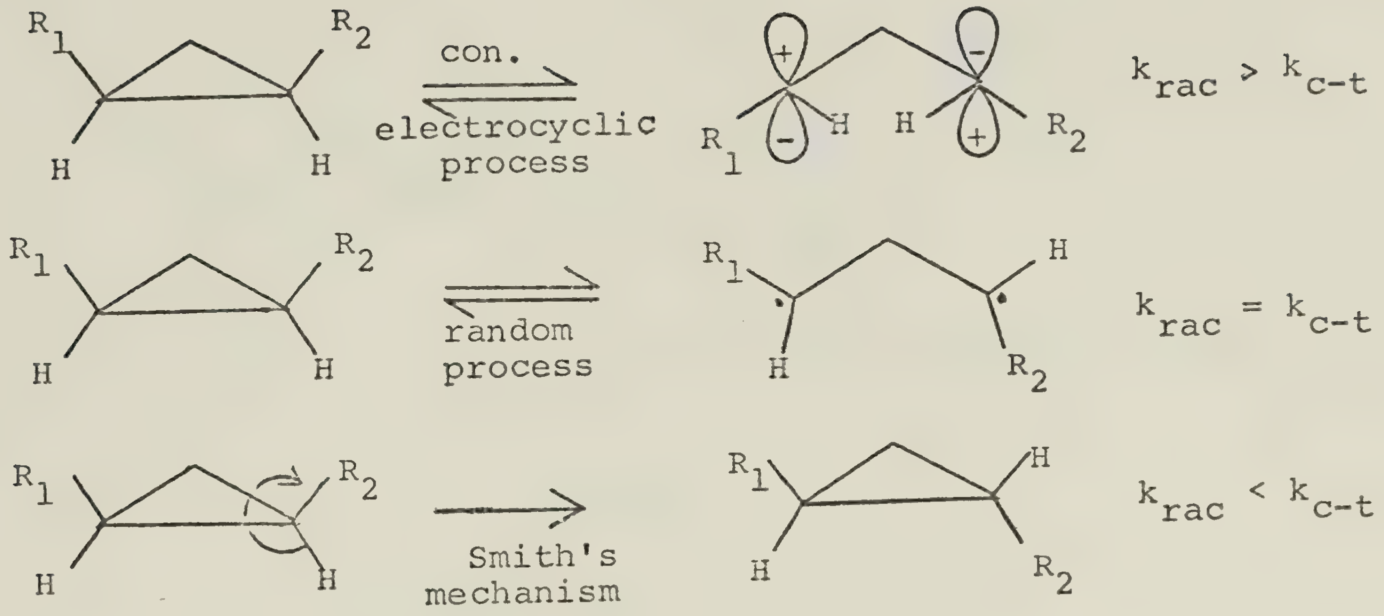
SCHEME 4

Lately a third type of cyclopropane thermal isomerization has been investigated, that is optical, or the racemization process.



The relation between rate constants for geometrical and optical isomerization should provide an answer to whether an electrocyclic process plays a major role in *cis-trans* isomerization, and whether a conrotatory mode of ring opening is a more favored process for the formation of the trimethylene intermediate than is a random or non-concerted process.

Scheme 5 shows three extreme mechanisms for these isomerizations, together with predicted magnitudes of rate constants for geometrical and optical isomerizations.

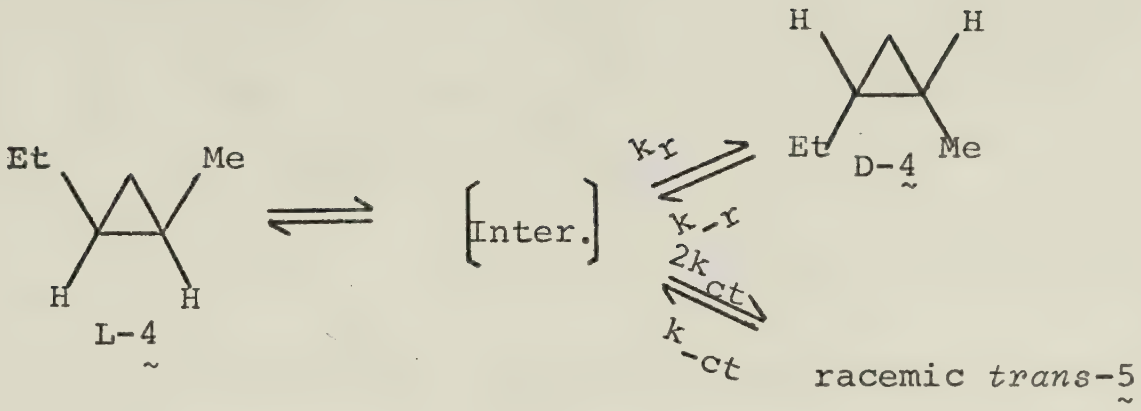


SCHEME 5

Berson and Balquist (23) studied racemization and geometrical isomerization of tetramethylcyclopropane-d_6 and found that these two processes occur at the comparable rates. They concluded that neither an intermediate of randomized stereochemistry, nor Smith's mechanism can be the only process, and that only a small fraction of ring-cleavage is an electrocyclic process.

Crawford and Lynch (24) reached a similar conclusion in their study of *trans*-1,2-diphenylcyclopropane, where the ratio of k_{rac}/k_{t-c} was found to be 1.51 at 229°.

Bergman and Carter (25) studied geometrical and optical isomerization of *cis*-1-ethyl-2-methylcyclopropane (4) and *trans*-1-ethyl-2-methylcyclopropane (5). Considering Scheme 6,



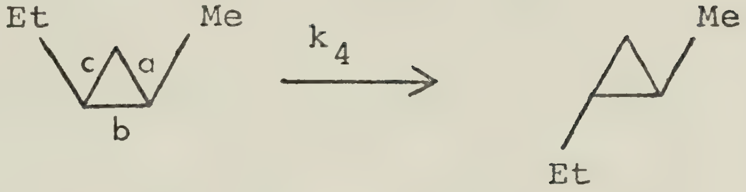
SCHEME 6

they were able to obtain the ratio $\frac{k_r}{k_{ct}}$.

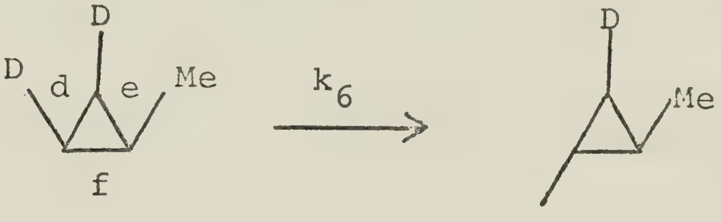
If the electrocyclic process plays a major role, this ratio should have value greater than 1 (in the case of pyrazolines this ratio is 2.86), i.e. racemization process must be faster than the geometrical isomerization. Assuming that only secondary-secondary bond cleavage is important, a value of 0.79 was obtained, which led to the conclusion that a concerted electrocyclic process, if it takes place at all, does so to a very small extent. The authors however neglected the possibility of primary-secondary bond cleavage, a path which can contribute to the over-all process of *cis-trans* isomerization. One can demonstrate that this possibility cannot be readily dismissed.

The isomerization of 4 can occur by cleavage of bonds a, b and c by rate constants $k_a + k_b + k_c = k_4$. Elliot and Frey (26) have measured k_4 and found log A = 15.08,

$E_a = 58.9$ kcal/mol.

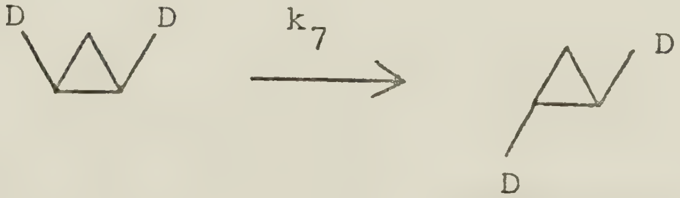


An estimate of $k_a + k_c$ can be made from the reaction of *cis*-1,2-dideuterio-3-methylcyclopropane (6):



6

measured by Setser and Rabinovitch (3d), (log A = 15.35 and $E_a = 60.5$ kcal/mol). If we assume that $k_a + k_c = k_e + k_f$, i.e., that the effect of CH_3- and C_2H_5- are comparable, and evaluate $k_d = 1/3\ k_7$, where k_7 is known from the work of Schlag and Rabinovitch (3b), (log A = 16.41; $E_a = 65.1$ kcal/mol).



The ratio of k_6/k_7 at 400° then is:

$$\log k_6/k_7 = 15.35 - 16.41 - \frac{(60.5 - 65.1)}{2.303\ RT}$$

$$\log k_6/k_7 = -1.06 + 1.49 = 0.43$$

$$k_6/k_7 = 2.7 \qquad \text{since } 3k_d = k_7$$

then

$$k_6/k_d = 8.1 \qquad k_d = 0.124\, k_6$$

$$k_6 = k_d + k_e + k_f \qquad k_6 = 0.124\, k_6 + k_e + k_f$$

$$0.876\, k_6 = k_e + k_f$$

$$\therefore \frac{k_e + k_f}{k_6} = 0.876 = \frac{k_a + k_c}{k_6}$$

Comparing observed rate for $\underset{\sim}{4}$ and $\underset{\sim}{6}$ at 400°C.

$$\log k_6/k_4 = 15.35 - 15.08 - \frac{(60.5 - 58.9)}{2.303\ RT}$$

$$= 0.27 - 0.52$$

$$= -0.25$$

$$k_6/k_4 = 0.56 \quad \therefore \frac{k_a + k_c}{k_4} = 0.876 \times 0.56 = 0.49$$

thus cleavage of bonds a + c can represent 49% of the observed reaction.

Since the observed rate for geometrical isomerization may in fact be composed of three rate constants, comparison of only k_b with the rate for the racemization process would be meaningful. Thus there is doubt about the authors conclusion.

While the intermediacy of a O,O-trimethylene species

is reasonable in the thermolysis of 1-pyrazolines (20) fragmentation of thietanonium salts (21) and deamination of azetidines (22) it is much more difficult to establish in the thermolysis of cyclopropanes. The possibility of the 0,90-trimethylene species, similar to that suggested by Smith (6), cannot be readily dismissed from playing a role in these reactions.

D. Thermal isomerization of oxiranes.

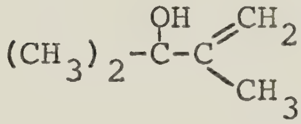
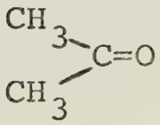
Thermal behaviour of oxirane (7) (27), 2-methyloxirane (8) (28), and 2,2,3,3-tetramethyloxirane (9) (29), has been studied. Pyrolysis of 7 and 8 is complicated by primary and secondary radical processes in addition to non-radical reactions. Thermal decomposition of 9, at a pressure of 11 torr is a first order, homogenous unimolecular reaction.

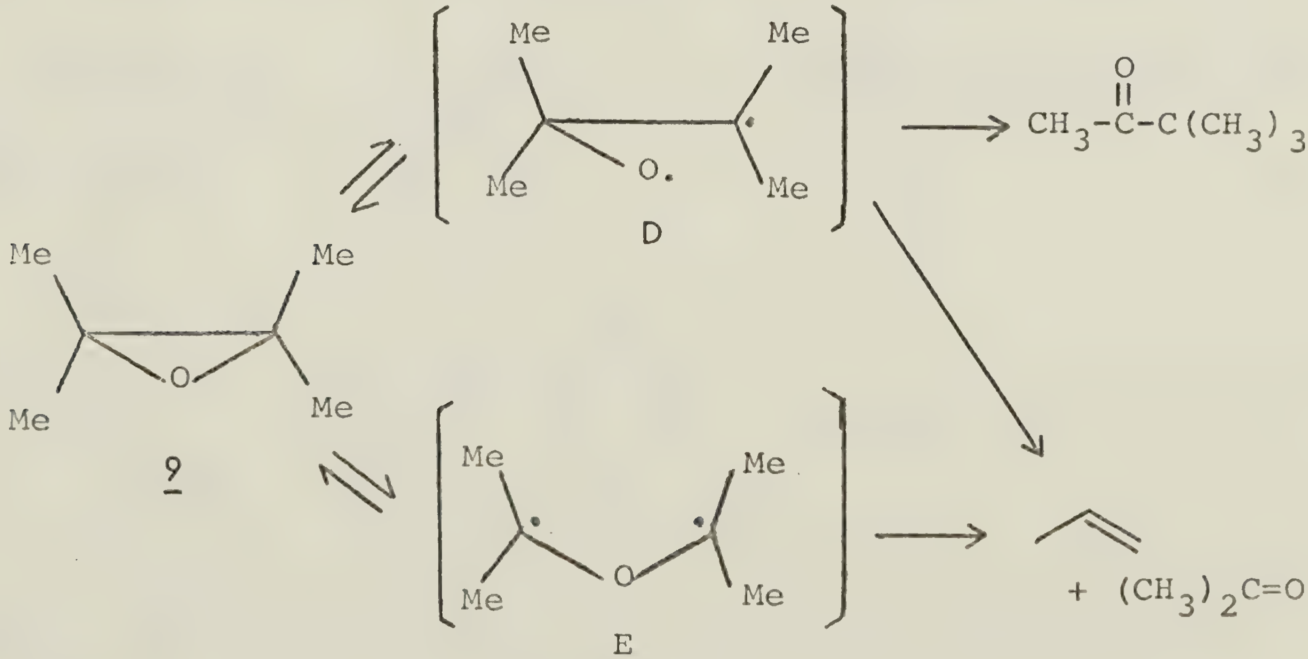
Activation parameters and products in these pyrolyses are shown in Table II.

The mechanism has been discussed in terms of initially formed diradicals, produced by the fission of either a carbon-carbon, or a carbon-oxygen bond (29). The diradical intermediate can either rearrange or decompose to give the observed products (Scheme 7).

TABLE II

Activation Parameters and Products in the Pyrolyses of 7, 8 and 9

Compound	Products	log A	E_a (kcalmol)	Ref.
7	CH_3CHO	14.34	57.4	27
8	CH_3CH_2CHO $+ CH_3COCH_3$	12	51.9	28
	 $(CH_3)_2C(OH)C(=CH_2)CH_3$	10.88	47.5	
9	 $(CH_3)_2C=O$	14.77	59.2	29
	$(CH_3)_3C-COCH_3$	13.81	56.7	



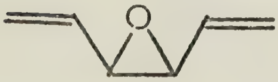
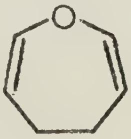
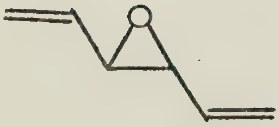
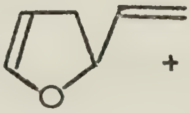
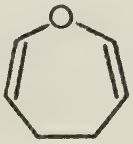
SCHEME 7

Based on thermodynamic calculations carbon-oxygen bond cleavage is favored over carbon-carbon bond rupture in the case of simple unsubstituted oxirane. However, with substitution the energy requirement becomes the reverse, and the formation of diradical E is favored over diradical D. Still, the intervention of diradical D is necessary to explain formation of 3,3-dimethyl-2-one in the pyrolysis of **9**.

The thermal behaviour of *trans*-2,3-divinyloxirane (**10**) and *cis*-2,3-divinyloxirane (**11**) was investigated (30)

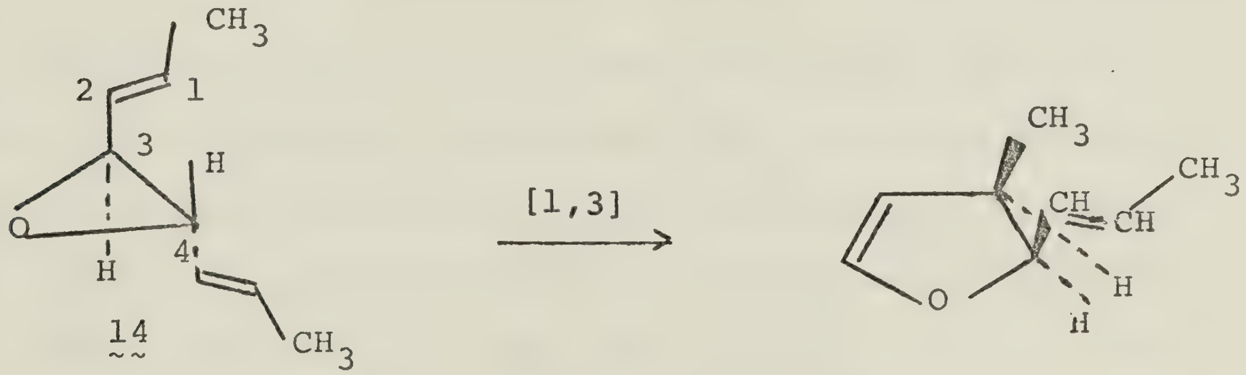
TABLE III

Activation Parameters and Products in the Thermolysis of **10** and **11**

Compound	Products	$\Delta H^{\ddagger}$ (kcal/mol)	$\Delta S^{\ddagger}$ e.u.
 **11**	 **12**	24.6	-11.3
 **10**	 +  **13** (70%) **12** (30%)	36.0	- 0.4

and found to be very similar to that of 1,2-divinylcyclopropane (**2**). The *cis*-oxirane (**11**) appears to be more stable than its cyclopropane analog, but rearranges at temperature above 50° to a single compound 4,5-dihydrooxepine (**12**). The low activation energy and negative entropy indicate a concerted transition state. Compound **10** at the temperature above 180° rearranges to two products: 2-vinyl-2,3-dihydrofuran (**13**) and **12**, in contrast to **2** which does not give rise to a five-membered ring product. (Table III).

Recently the study of the thermal rearrangement of several 2,3-divinyloxiranes, substituted at the double bond, has been reported (31). It was found that the conversion of 2,3-dipropenyloxirane (**14**) to 2-propenyl-3-methyl-2,3-dihydrofuran is a concerted 1,3-sigmatropic rearrangement.



Since **14** was optically inactive, the question of whether this rearrangement proceeds in an antarafacial manner with retention of configuration, or in a suprafacial manner with the inversion of configuration at the migration center (C-4), could not be answered.

E. Theoretical considerations of oxa-trimethylene.

The ring-open form of oxirane represents a 4π electron system, since a lone pair on oxygen is mixing with S combination of terminal $-CH_2$ orbitals (18).

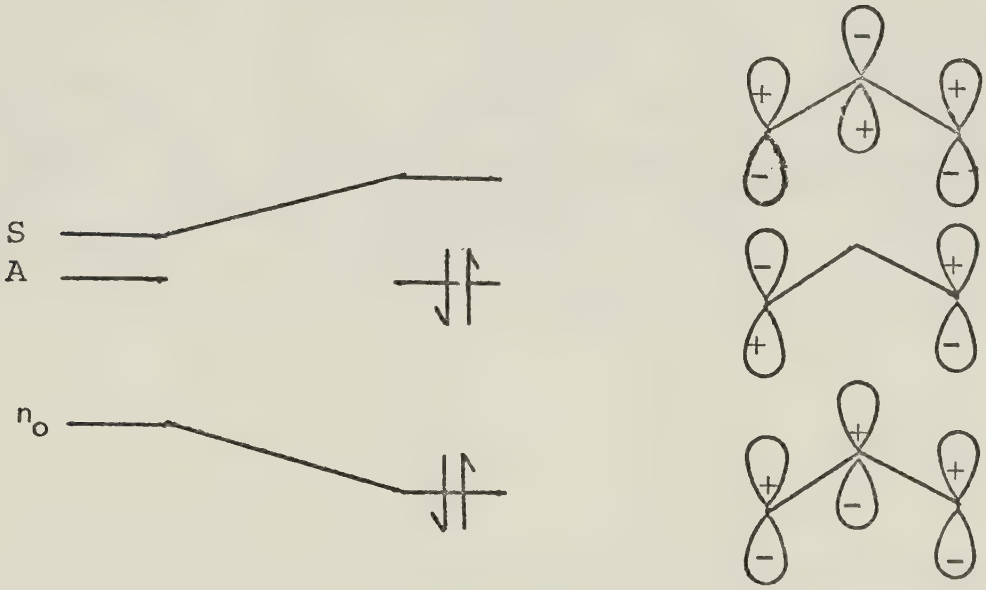
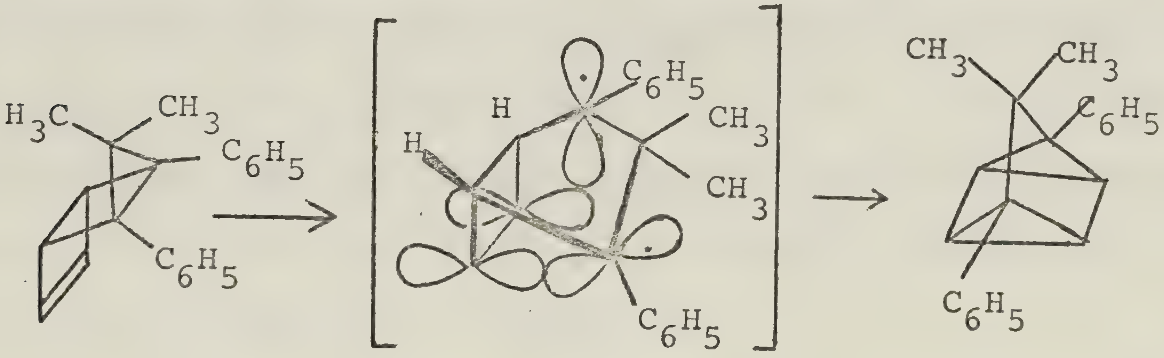


FIGURE 2. An Interaction Diagram for Oxa-trimethylene.

This diagram is similar with the one for the allyl anion and consequently conrotatory mode of closure of this species to its three-member analog is predicted. Preference for conrotatory closure should be more pronounced than in the case of trimethylene since the splitting of the S and A level is much greater. Another consequence of such an electronic structure is a concerted addition to (4n + 2) π electron systems.

Cycloaddition of trimethylene to a double bond has never been observed on an intermolecular basis and the only reported case is the intramolecular trapping of trimethylene

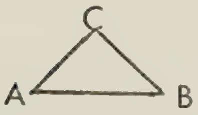
diradical in the conversion of I to II, though the mechanism has not yet been established, however concerted process is orbital-symmetry forbidden (32).



I II

On the other hand cycloaddition of tetracyanooxirane to olefins is known to occur in a highly stereospecific manner and is insensitive to solvent polarity and substitution changes (33).

Recently a theoretical study of the electronic structures of the open forms of several three membered rings has been carried out (34).



A=B=C = $-CH_2$

A=B = $-CH_2$, C= -0-

A=B = $-CH_2$, C= -NH-

A= $-CH_2$, B= -0-, C= -NH-

A=B=C= -0-

The electronic structure of the open form of these species

is a linear combination of resonating π-system $B=\overset{+}{A}-\overset{-}{C} \longleftrightarrow \overset{-}{B}-\overset{+}{A}=C$ and a π-diradical $\dot{B}-A-\dot{C}$. Concerted mode of reaction of these species is understood as the concerted ring opening and a concerted cycloaddition. The higher percentage of a diradical character means a smaller fraction of the electronic wavefunction has a stereochemical preference. These calculations have been carried out using non-empirical self consistent field and configuration interaction methods, and the results are summarized in Table IV.

TABLE IV

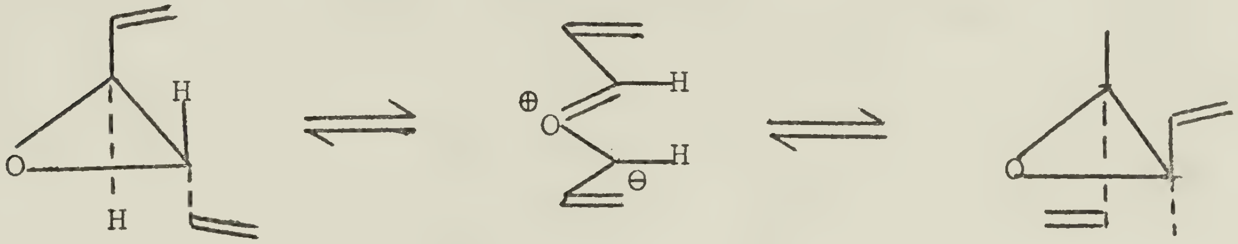
π-diradical Character of the Open Forms of Several Three Membered Rings

Molecule	Calculated weight π_+^2	π_-^2*	Diradical Character
Cyclopropane	40%	60%	80%
Cyclopropyl anion	4%	96%	8%
Aziridine	15%	85%	30%
Ethylene oxide	19%	81%	38%
Oxazirane	10%	90%	20%
Ozone	15%	85%	30%

* π_+ signifies that the p-π atomic orbitals on the terminal atoms, both enter the molecular orbital with a positive coefficient, and π_- signifies a negative coefficient.

PROBLEM

The controtatory mode of ring opening for *trans*-2,3-divinyl oxirane **10** produces an oxa-trimethylene (**15**) which is isoelectronic with heptatrienyl anion, and is a planar racemic intermediate. Ring closure should thus generate racemic **10** and is a process which may be followed polarimetrically.



10 **15**

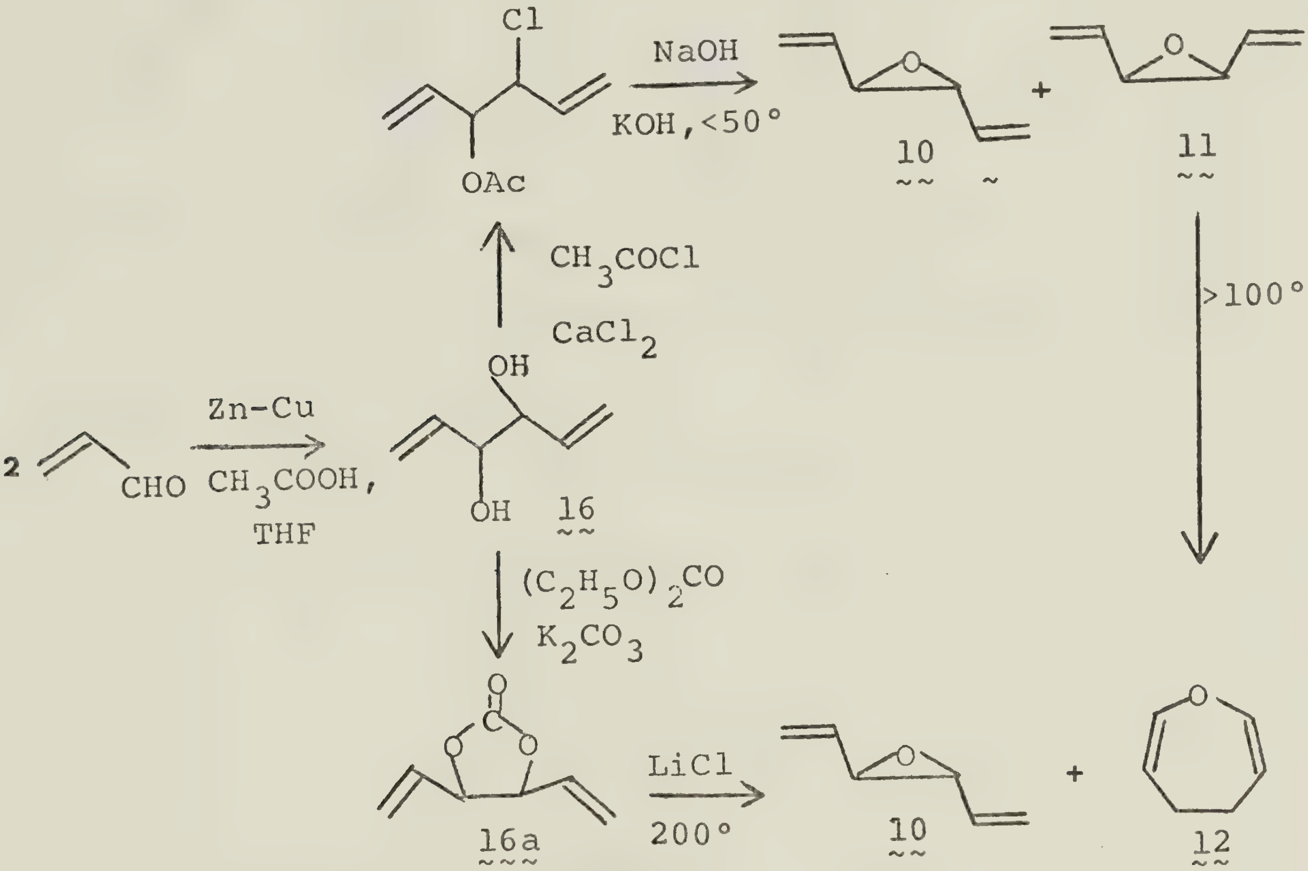
The oxirane **10** is also capable of *trans* to *cis* isomerization. This geometrical isomerization may proceed via a Smith type of transition state or via a conrotatory ring opening followed by a less probable disrotatory ring closure (or *vice-versa* a disrotatory opening and a conrotatory closure). By studying both the racemization and the *trans*-to-*cis* isomerization of **10** we obtain an indication of the feasibility of each reaction. By comparison of the data thus obtained with that of Dr. Mannosuke Arai for **2** some insight into the isomerization of the latter may be obtained.

Since the isomerization of **10** into **13** occurs at a comparable rate to *trans*-to-*cis* isomerization, there is possibility that we may obtain insight into the mechanism by which the latter is formed, when we use optically active **10**.

RESULTS

A. Synthesis and Resolution of *trans*-2,3-divinyloxirane **10**.

The oxirane **10** was prepared by the method of Braun (35) and Stogryn (36), as indicated in Scheme 8.



SCHEME 8

Under the conditions employed **11** is converted to **12**. Separation of **10** and **12** was achieved by preparative gas chromatography, using a ten foot column of 15% β,β'-oxidipropionitrile on firebrick.

Spectral data for **10** were in agreement with those previously published. The nmr spectrum in deuteriochloroform (Figure 3) showed two sets of protons in a ratio of 3:1.

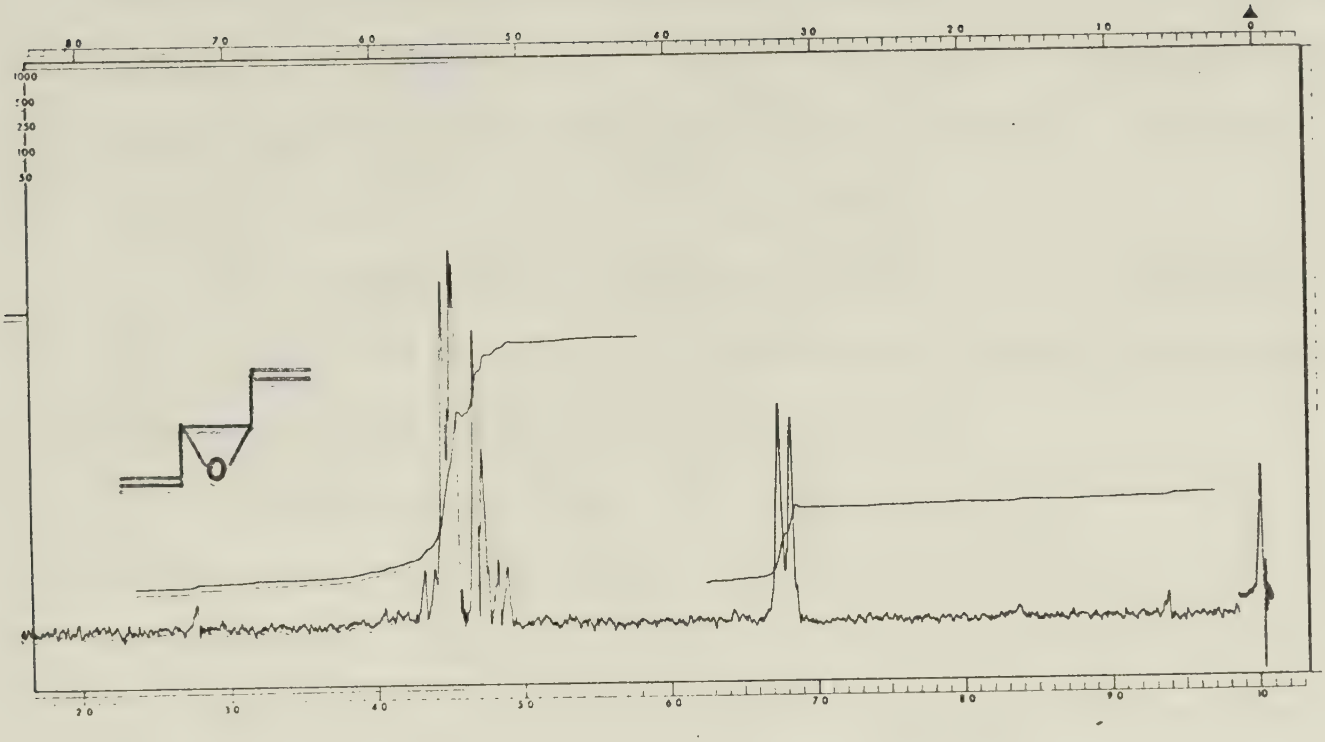


FIGURE 3. Solvent $CDCl_3$

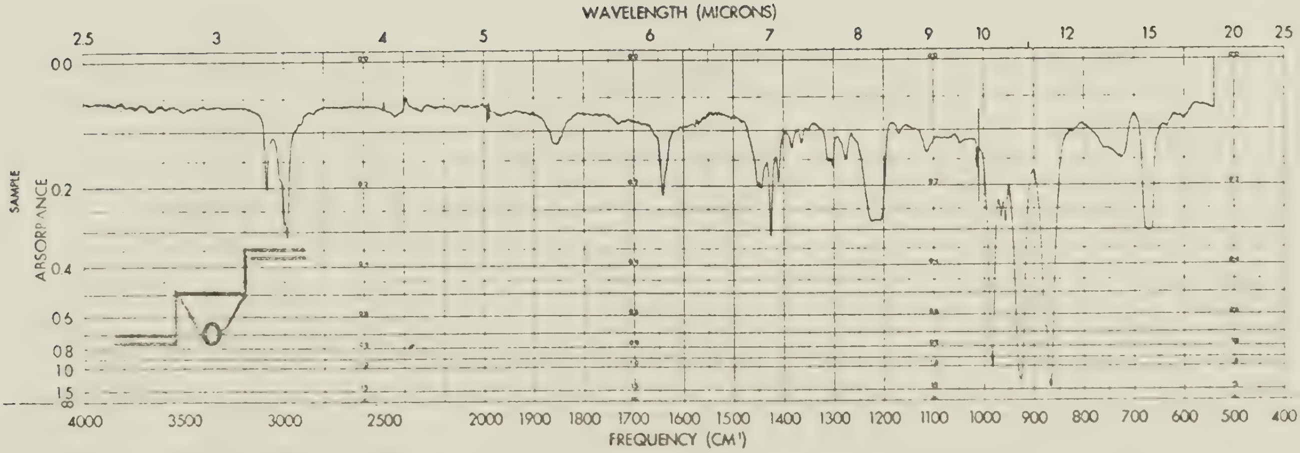


FIGURE 4 Solvent $CHCl_3$

The vinyl protons are multiplet centered at τ 4.55 and ring protons are a doublet at τ 6.75. IR spectrum in chloroform showed the following infrared maxima: 10.17(s), 10.82(s), 11.38(s), 11.50(s) and 14.79(s), (Figure 4).

The oxirane **10** was then subjected to one equivalent of di-3-pinanylborane at -20°, to achieve partial asymmetric destruction, as described by Brown (37).

Since oxiranes react with borane at 0°, though at a slower rate than the double bond (38), the normal procedure was modified. The unreacted **10** was then isolated using preparative gc. Specific rotations for **10** are shown in Table V.

TABLE V

Specific Rotations for 2,3-divinyloxirane **10**

Wavelength (mμ)	α^{obs} (10.2 g/100 ml, 2-propanol)	$[\alpha]_{m\mu}^{26°}$
578	-0.079°	-0.78°
546	-0.102°	-1.00°
436	-0.299°	-2.94°
365	-0.744°	-7.29°

B. Kinetic Studies

The decrease of optical activity of **10** with time, was followed at three different temperatures, as described in

the Experimental section. Correction for residual rotation was applied. Plot of log $\frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty}$ *vs.* time showed in all cases good first-order kinetics.

The rate constants were obtained from the data in the following manner. For a first-order gas phase reaction of the type A → products, it is known that,

$$k = 2.303/t \times \log \frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty} \qquad (1)$$

where k is the first order constant, t is the time, $[\alpha]_o$ is the specific rotation of $\underset{\sim\sim}{10}$ at t = 0, $[\alpha]_t$ is the specific rotation of $\underset{\sim\sim}{10}$ after being heated for time t, $[\alpha]_\infty$ is the residual rotation after more than 10 half-lives. A plot of log $\frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty}$ *versus* t gives a straight line with a slope equal to k/2.303.

To obtain an indication of the error limits associated with the best-fit values of the constants in a linear equation the least squares method of numerical solution was used (39).

Equation (1) has the form,

$$y = bx + a \qquad (2)$$

where $y = \log\frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty}$; $b = k/2.303 = \frac{n\sum xy-\sum x\sum y}{n\sum x^2-(\sum x)^2}$

$x = t$, and intercept $a = \dfrac{\sum x^2 \sum y - \sum x \sum xy}{n\sum x^2 - (\sum x)^2}$

The probable error in b is P_b given by

$$P_b = P_y \sqrt{\frac{n}{n\sum x^2 - (\sum x)^2}} \qquad (3)$$

where

$$P_y = 0.6745\sqrt{\frac{\sum (y-a-bx)^2}{n-2}} \qquad (4)$$

TABLE VI

Decrease of Optical Activity of 10 with Time and the Least Squares Calculation for the Rate Constant at 150.04°C

Temperature 150.04 ± 0.03°, $[\alpha]_o = -5.670°$, $[\alpha]_\infty = -0.600°$

Sample No. n	Time (min) x	$-[\alpha]_t$	$\log \dfrac{[\alpha]_t - [\alpha]_\infty}{[\alpha]_o - [\alpha]_\infty}$ y
1	60	5.010	0.061
2	120	4.236	0.144
3	180	3.498	0.243
4	298	2.685	0.386
5	420	1.835	0.613

$\sum x = 1078$, $\sum y = 1.447$, $\sum x \sum y = 1559.866$, $(\sum x)^2 = 1162084$

$\sum xy = 437.168$, $\sum x^2 = 315604$, $\sum x^2 \sum y = 456678.988$,

$\sum x \sum xy = 471267.104$, $b = 15.04976 \times 10^{-4}\ \text{min}^{-1}$,

$a = -350.7298 \times 10^{-4}$, $\sum(y-a-bx)^2 = 109391 \times 10^{-8}$

$P_y = 12.87977 \times 10^{-3}$, $P_b = 0.44655 \times 10^{-4}$.

Thus

$$k = \frac{b \times 2.303}{60} = 5.77 \times 10^{-5} \text{ sec}^{-1}$$

Error in k is given by:

$$\frac{P_b \times 2.303}{60} = 0.17 \times 10^{-5} \text{ sec}^{-1}$$

Thus $k = 5.8 \pm 0.2 \times 10^{-5}$ sec^{-1} obtained by the least squares analysis agrees well with the value of 5.9×10^{-5} sec^{-1} obtained from the graphical plot (Figure 5).

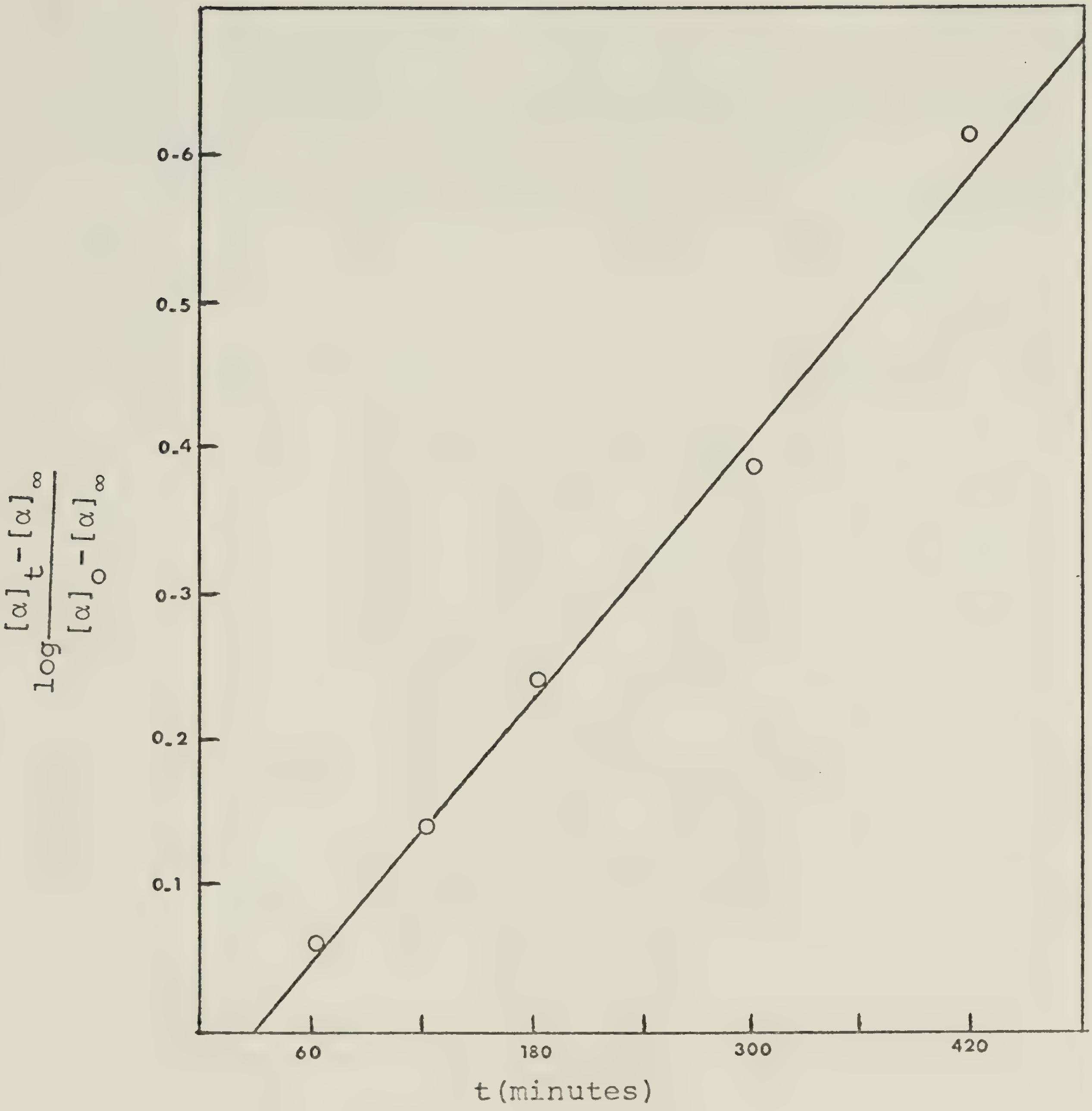


FIGURE 5 Plot of $\log\frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty}$ *versus* t for **10** at 150.04°

TABLE VII

Decrease of Optical Activity of 10 with Time and the Least Squares Calculation for the Rate Constant at 160.07°.

Temperature 160.07 ± 0.04°, $[\alpha]_o = -5.670°$, $[\alpha]_\infty = -0.600°$.

Sample no. n	Time (min) x	$-[\alpha]_t$	$\log \frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty}$ y
1	40.2	4.344	0.132
2	90	3.224	0.286
3	150	2.518	0.422
4	209	1.717	0.657
5	300	1.239	0.900

$\sum x = 789.2$, $\sum y = 2.397$, $\sum x \sum y = 1891.7124$, $(\sum x)^2 = 622836.64$

$\sum xy = 501.6594$, $\sum x^2 = 165897.04$, $\sum y \sum x^2 = 397655.2048$

$\sum x \sum xy = 395909.59848$, $b = 29.8373 \times 10^{-4}$, $a = 84.4722 \times 10^{-4}$

$\sum (y-a-bx)^2 = 188612 \times 10^{-8}$, $P_y = 16.912 \times 10^{-3}$,

$P_b = 0.8311 \times 10^{-4}$.

Thus $k = 11.4 \pm 0.3 \times 10^{-5}$ sec^{-1} obtained by the least squares analysis agrees with the value of 11.5×10^{-5} sec^{-1} obtained from the graphical plot (Figure 6).

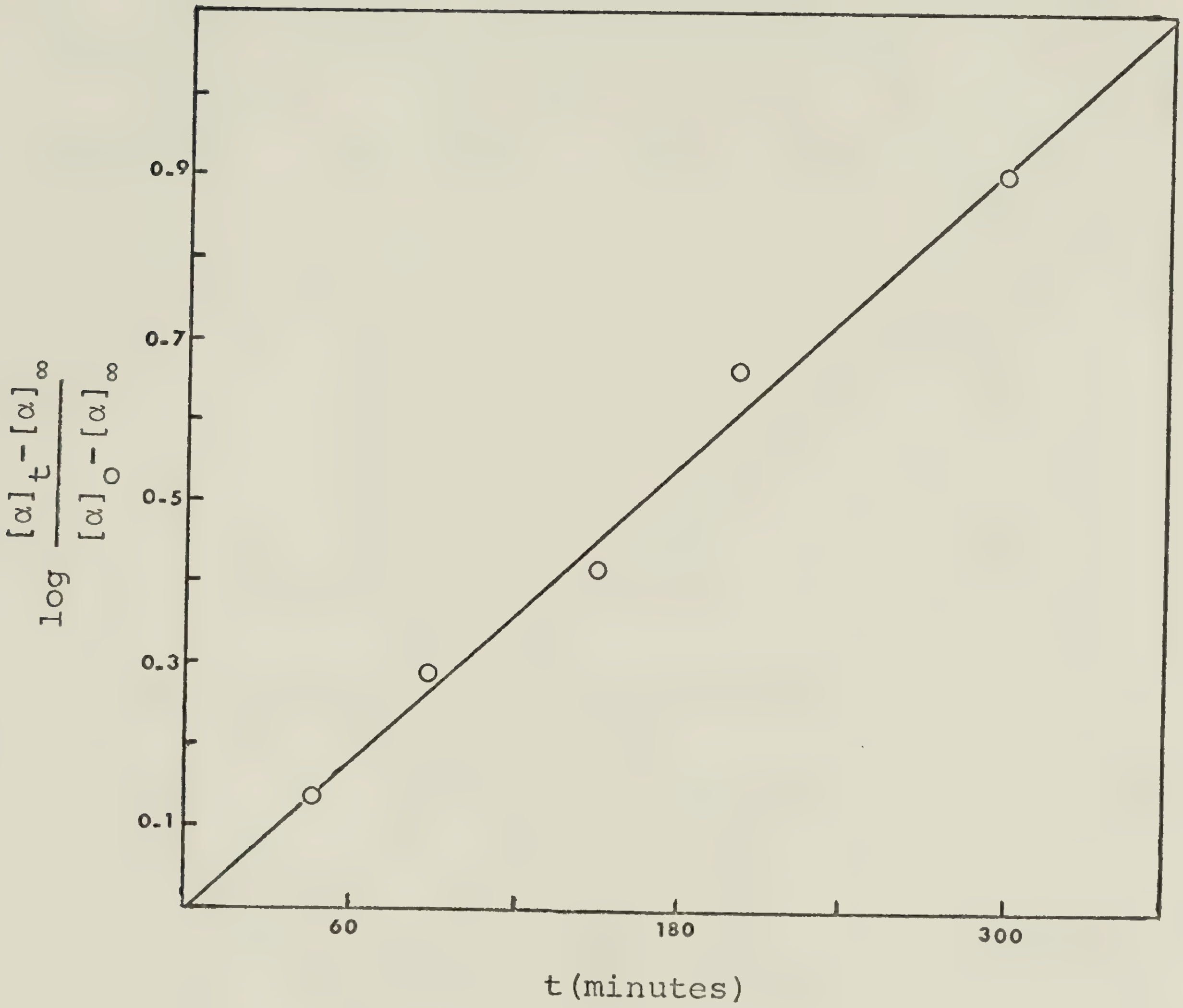


FIGURE 6. Plot of $\log \frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty}$ *versus* t for 10 at 160.07°

TABLE VIII

Decrease of optical activity of **10** with time and the least squares calculations for the rate constant at 171.55°.

Temperature 171.55 ± 0.07°, $[\alpha]_t = -5.670°$, $[\alpha]_\infty = -0.600°$

Sample no. n	Time (min) x	$-[\alpha]_t$	$\log \frac{[\alpha]_t - [\alpha]_\infty}{[\alpha]_o - [\alpha]_\infty}$ y
1	32	3.739	0.208
2	47.3	2.515	0.423
3	62.3	2.268	0.483
4	92	1.484	0.759
5	117	1.204	0.924

$\sum x = 350.6$, $\sum y = 2.797$, $\sum x \sum y = 980.6282$, $(\sum x)^2 = 122920.36$, $\sum xy = 234.6908$, $\sum x^2 = 29295.58$, $\sum x \sum y^2 = 81939.73726$, $\sum x \sum xy = 82282.59448$, $b = 81.8531 \times 10^{-4}$, $a = -145.5403 \times 10^{-4}$, $\sum (y-a-bx)^2 = 502934 \times 10^{-8}$, $P_y = 27.6170 \times 10^{-3}$, $P_b = 4.0233 \times 10^{-4}$.

Thus $k = 31.4 \pm 1.5 \times 10^{-5}$ $\sec^{-1}$, obtained by the least squares analysis agrees with the value of 31.2×10^{-5} $\sec^{-1}$ obtained by the graphical plot. (Figure 7). Error of 4.5% is derived from the difficulty in maintaining a constant high temperature, when placing samples into a constant-temperature bath.

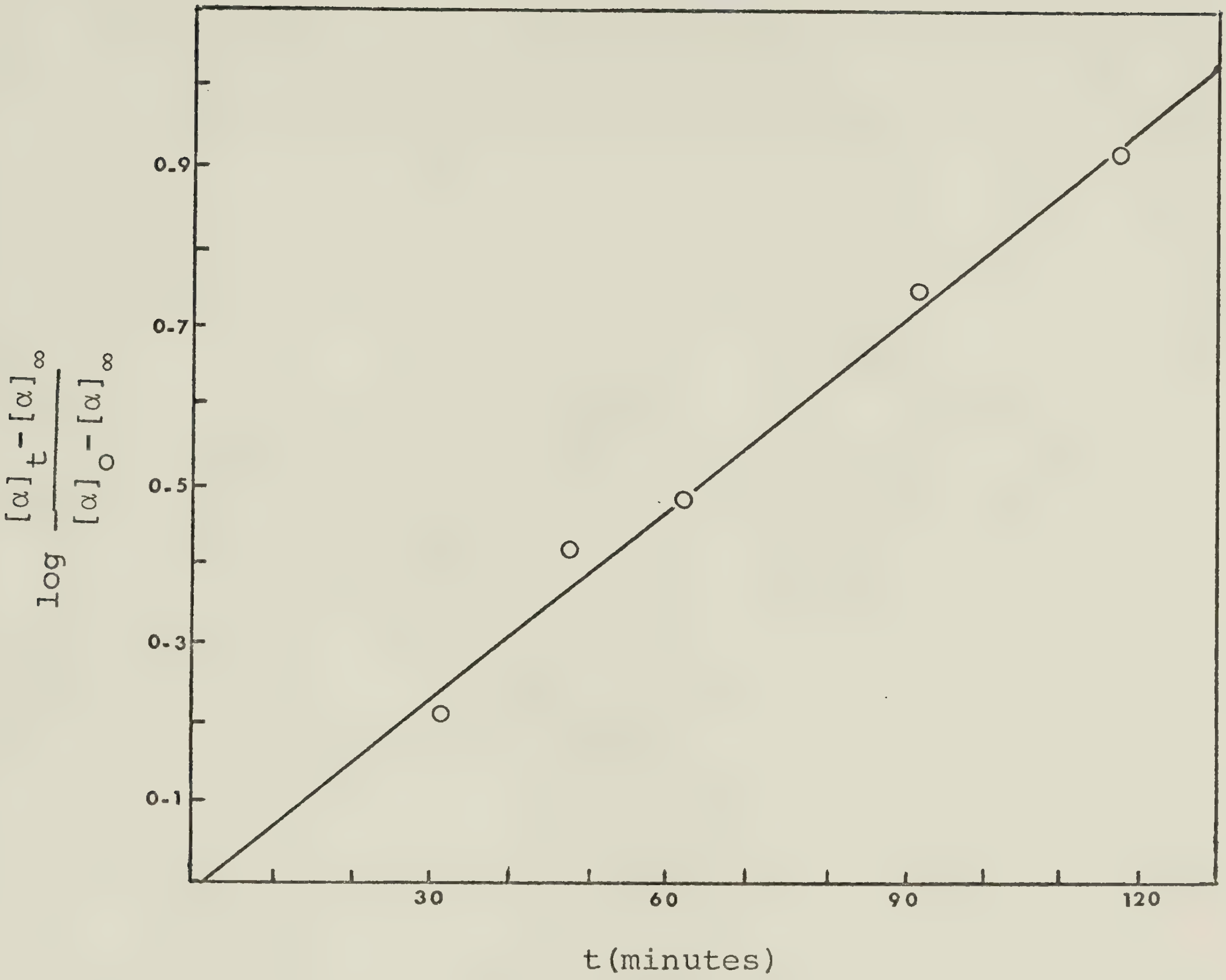
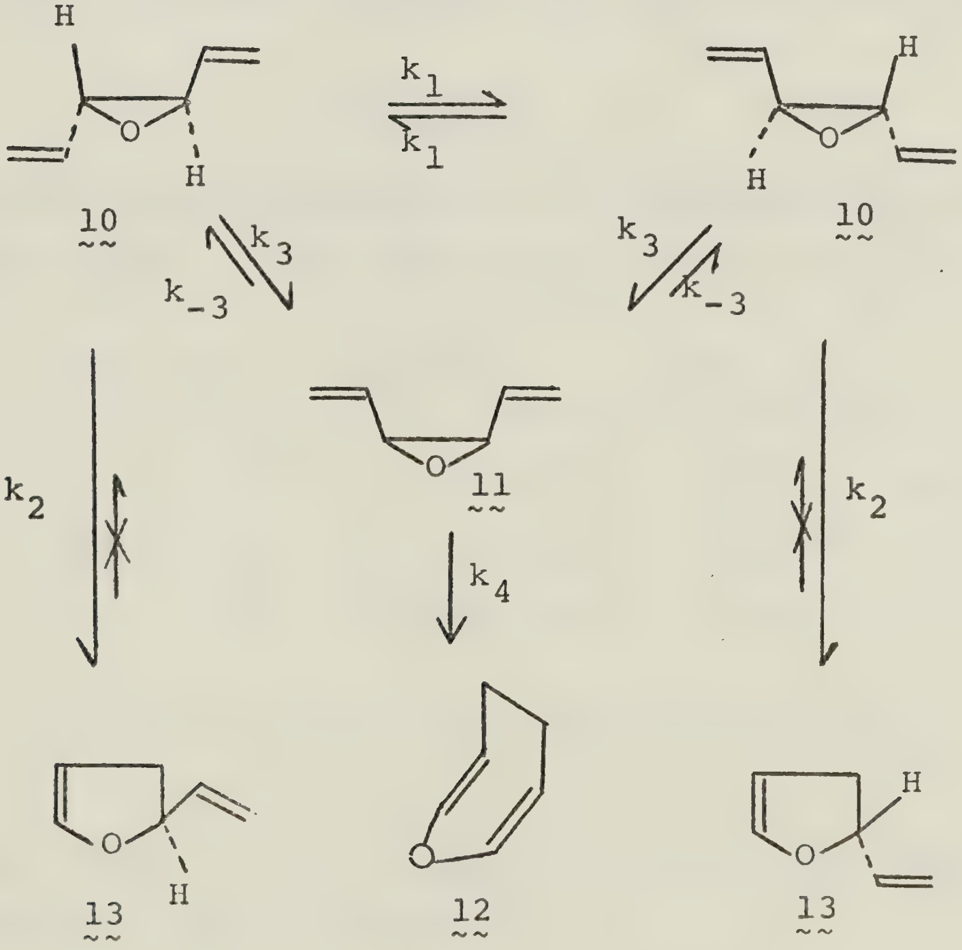


FIGURE 7. Plot of log $\frac{[\alpha]_t-[\alpha]_\infty}{[\alpha]_o-[\alpha]_\infty}$ *versus* t for the decrease of optical activity of **10** at 171.55°C

Each of the observed rate constants for racemization of 10 is in fact composed of three rates, one for the interconversion of two enantiomers and the other two for the formation of two geometrical isomers. These contribute to the over-all decrease in optical activity as shown in Scheme 9.



SCHEME 9

It is known that 11 is converted to 12 at 60° (36), with no 10 being produced, thus we know that $k_4 > k_{-3}$. From

the data in Table III in the historical section, it can be calculated that $k_4 \geq 10^4 k_3$ at 160°. There is implicitly the suggestion that $\underset{\sim\sim}{12}$ is produced only *via* $\underset{\sim\sim}{11}$, but this does not affect the general scheme.

Thus

$$k_{obs} = 2k_1 + k_2 + k_3$$

From the data published earlier (30), it is possible to evaluate $k_2 + k_3$, and these are shown in Table IX.

TABLE IX

First Order Rate Constants for the Geometrical and Racemization Process in the Thermolysis of $\underset{\sim\sim}{10}$ (in sec^{-1}).

Run no.	Temp (°C)	$10^5 k^{obs}$	$10^5 (k_2 + k_3)$	$10^5 k_1$
1	150.04 ± 0.03	5.77 ± 0.17	0.13	2.82 ± 0.08
2	160.07 ± 0.04	11.45 ± 0.31	0.37	5.54 ± 0.15
3	171.55 ± 0.07	31.41 ± 1.55	1.14	15.13 ± 0.77

The effect of the temperature on the rate constant is given by the Arrhenius equation:

$$k = Ae^{-Ea/RT} \tag{5}$$

where Ea is the activation energy and A is the frequency factor. Equation (5) can be expressed in the logarithmic

forms (6) and (7)

$$\ln k = \ln A - Ea/RT \tag{6}$$

or

$$\log k = \log A - \frac{Ea}{2.303R} \times \frac{1}{T} \tag{7}$$

The activation energy Ea is obtained from the slope of a plot of log k *vs.* 1/T and logarithm of frequency factor log A as the intercept (Figure 8).

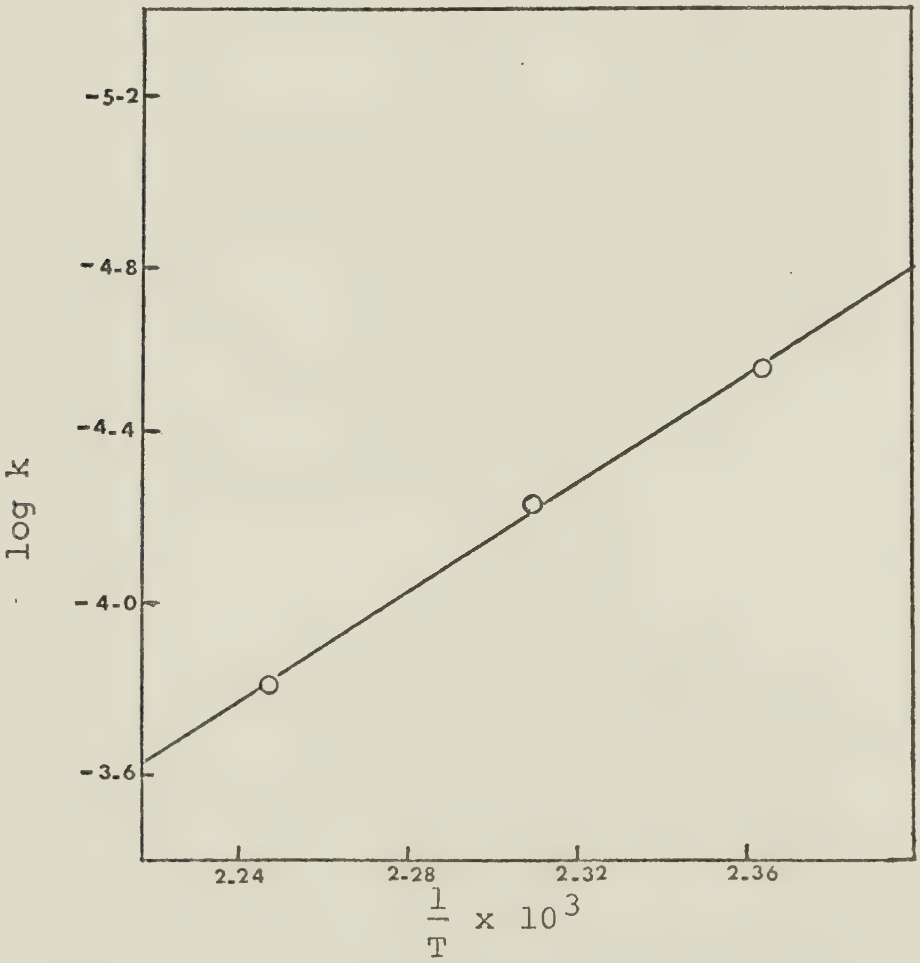


FIGURE 8. Plot of log k *vs.* 1/T for the racemization of 10.

Both parameters were calculated by the least squares analysis and the results are shown in Table X.

TABLE X

Least Squares Calculation of the Activation Parameters for the Racemization of 10.

Run No. n	log k y	1000/T x	x^2	xy	$(y-a-bx)^2 \times 10^{-8}$
1	-4.551	2.3630	5.5837	-10.7540	37713
2	-4.257	2.3082	5.3277	- 9.8260	139179
3	-3.821	2.2487	5.0566	- 8.5922	31990

$\sum y = -12.629$, $\sum x = 6.9199$, $\sum x \sum y = -87.3914$, $\sum x^2 = 15.9682$

$\sum y \sum x^2 = -201.6624$, $\sum x \sum xy = -201.86942$, $(\sum x)^2 = 47.8850$,

$P_y = 308.27 \times 10^{-4}$, $P_b = 3813.10 \times 10^{-4}$.

From the data in Table X

$$y = bx + a$$

$$-E_a/2.303R = b = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (\sum x)^2}$$

$$E_a = 29.28 \text{ kcal/mol}$$

$$\log A = a = \frac{\sum x^2 \sum y - \sum x \sum xy}{n\sum x^2 - (\sum x)^2}$$

$$\text{Log } A = 10.55$$

The error in activation energy E_a in kcal/mol can now be calculated

$$\text{Error} = P_b \times 2.303 \times 1.987 = \pm 1.74 \text{ kcal/mol}$$

For a gas phase reaction

$$\Delta H^{\ddagger} = E_a - nRT \qquad (8)$$

where $\Delta H^{\ddagger}$ is the enthalpy of activation and n is the order of the reaction. For the first order reaction equation (8) becomes

$$\Delta H^{\ddagger} = E_a - RT \qquad (9)$$

From the transition state theory (56)

$$k = \frac{k'T}{h} \times e^{-\Delta H^{\ddagger}/RT} \times e^{+\Delta S^{\ddagger}/R} \qquad (10)$$

where k' is Boltzmann's constant, h is Planck's constant, $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are the enthalpy and entropy of activation, respectively. Combining equations 8, 9 and 10, an expression for $\Delta S^{\ddagger}$ is obtained.

$$\Delta S^{\ddagger} = R \ln \frac{Ah}{k'Te} \qquad (11)$$

or

$$\Delta S^{\ddagger} = 2.303 R \left[\log \frac{h}{k'Te} + \log A\right] \qquad (12)$$

Equation 12 was used to calculate the entropy of activation at 160°C.

$$\Delta S^{\ddagger}_{160°} = 4.576\ (\log A - 10.3201 - 2.6365 - 0.4343)$$

$$= 4.576\ (10.55 - 13.3939)$$

$$= 4.576 \times (-2.8419)$$

$$= -13 \text{ e.u.}$$

The complete kinetic data for the racemization of 10 are given in Table XI.

TABLE XI

First Order Rate Constants (in sec^{-1}) and Activation Parameters for Racemization of 10.

Run no.	Temp. (°C)	$10^5 k_{rac}$	Activation Parameters
1	150.04 ± 0.03	2.8 ± 0.1	E_a = 29.28 kcal/mol
2	160.07 ± 0.04	5.6 ± 0.1	log A = 10.55
3	171.55 ± 0.07	15.1 ± 0.8	$\Delta S^{\ddagger}_{160°}$ = -13 e.u.

TABLE XII

Rotations* Exhibited by the Infinity Runs

Run no.	Time (hr)	α^{obs} (Conc. of **10** in %, 2-propanol)	$[\alpha]_\infty$
1	47	-0.060° (10.5)	-0.571°
2	117	-0.058° (9.85)	-0.588°
3	13	-0.063° (10.3)	-0.611°

* At 365 mμ

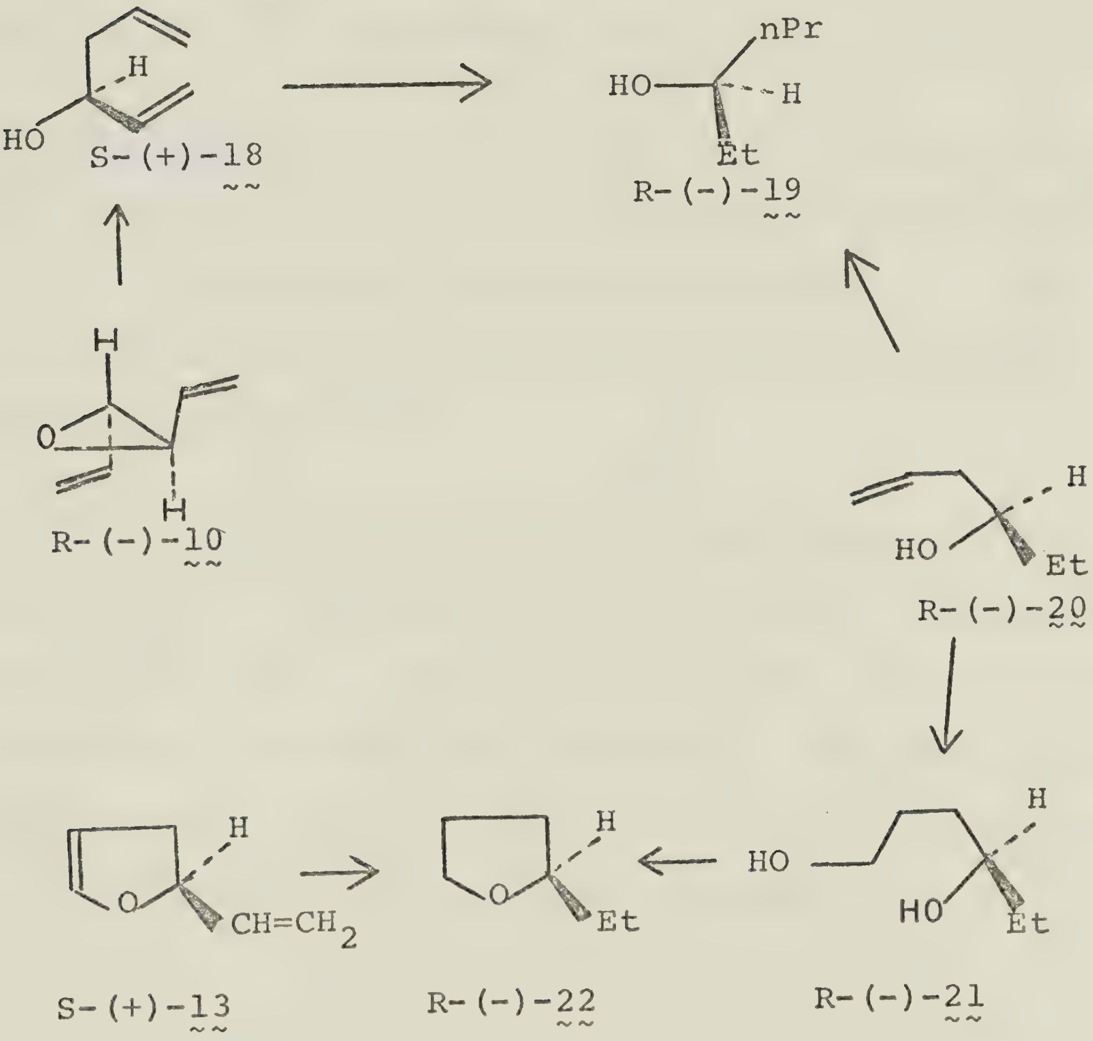
C. Absolute Configuration and Optical Purity of **10** and **13**.

Infinity samples, taken after more than 10 half-lives, exhibited residual rotation, as shown in Table XII, indicating formation of an optically active compound **13**. As estimated from the known rate constants and confirmed by the gc analysis **13** was formed in such a small amount at these temperatures, that its preparation and isolation in an optically active form by this route was not practical.

In order to test whether optically active **13** arises from **10** in a concerted process, i.e. 1,3-sigmatropic shift with inversion or retention of configuration, a comparison of their absolute configurations was made. This was done by the correlative method with 3-hexanol (**19**) as a reference compound. Its absolute configuration (40) and optical

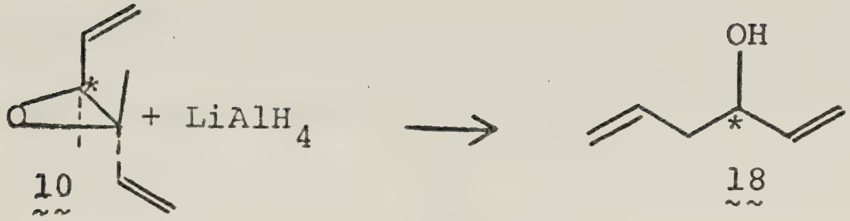
purity (41) are known.

Scheme 10 shows the absolute configurations of each of the compounds used in the sequence from R-(-)-**10** to S-(+)-**13**.



SCHEME 10

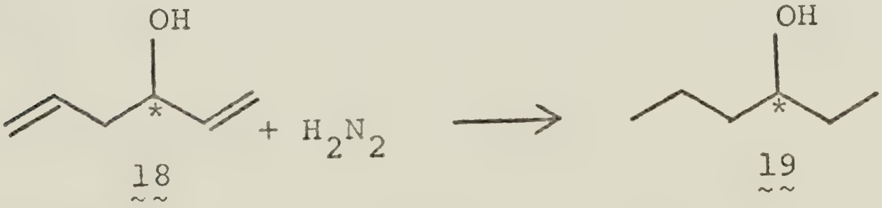
Reduction of R-(-)-**10** to S-(+)-1,5-hexadien-3-ol (**18**) was carried out with lithium aluminumhydride in dry ether.



Compound 18 was also prepared independently, resolved and used for further transformations.

Synthesis and resolution of S-(+)-18. This compound was prepared by the method of Butz (42), from allyl bromide and acrolein in the presence of magnesium in ether. It was resolved via the brucine salt of the phthalate half-ester, as described by Levin (43).

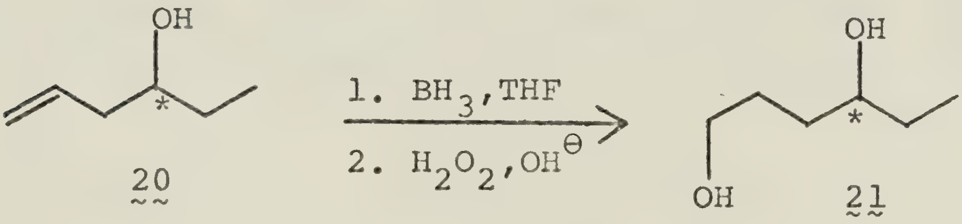
Hydrogenation of S-(+)-18 to R-(-)-19, was carried out first by the procedure described by Levin (43) in the presence of palladium on charcoal. The isolated products were identified as hexane, 3-hexanone and 3-hexanol. Since the extent of racemization of the semi-reduced form was not known, the diimide hydrogenation was carried out successfully.



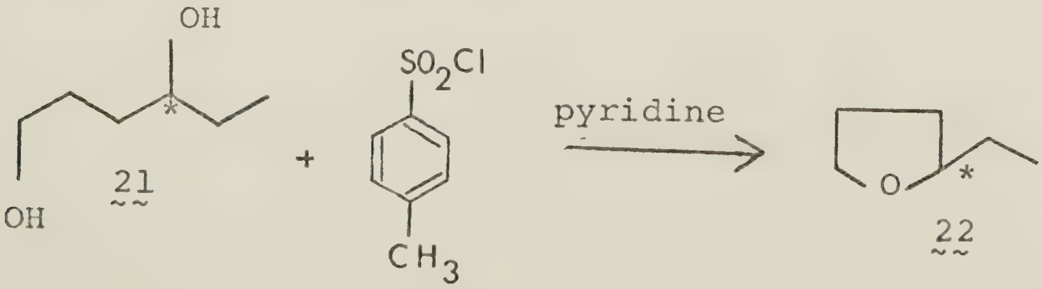
Synthesis and resolution of R-(-)-1-hexen-4-ol (20). This compound was prepared from allyl bromide, propionaldehyde and zinc in tetrahydrofuran (44). Resolution was carried out in the same manner as compound 18.

Hydrogenation of R-(-)-20 to R-(-)-19, was carried out under the conditions described for the conversion of 18 to 19.

Conversion of R-(-)-20 to R-(-)-1,4-hexandiol (21) was carried out employing Brown's method for the *anti*-Markovnikoff hydration of double bond (45).

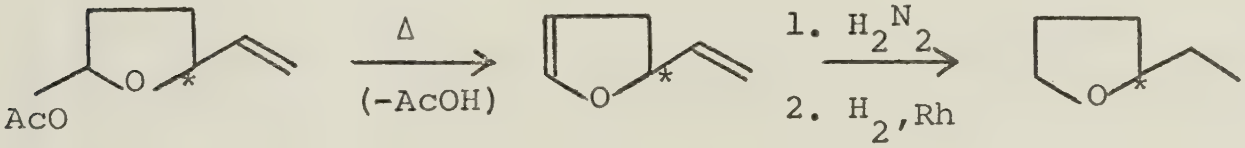


Conversion of R-(-)-21 to R-(-)-2-ethyl-tetrahydrofuran (22) was carried out by the method described by Coates (46). R-(-)-21 was treated with one equivalent of p-toluenesulphonylchloride in pyridine and under the conditions employed, cyclisation occurred spontaneously.



S-(+)-**13** was prepared via 2-vinyl-5-acetyltetrahydrofuran (**23**) by the procedure of Glacet (47). Compound **23** was subjected to a partial asymmetric destruction (37) and pyrolized to yield S-(+)-**13**. Reduction of S-(+)-**13** by diimide afforded optically active 2-ethyl-2,3-dihydrofuran, which yielded R-(-)-**22** after reduction with hydrogen in the presence of rhodium on charcoal.*

Absolute configurations, optical purity and sources of compounds **10**, **18**, **19**, **20**, **21**, **22** and **13** are shown in Table XIII.



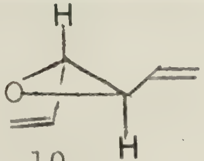
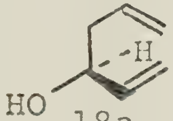
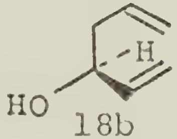
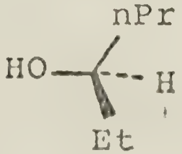
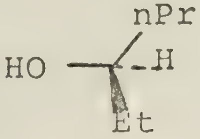
23 **13** **22**

---

*Preparation, resolution and reduction of **13** was carried out by Dr. Hirokazu Tokunaga of this laboratory.

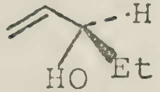
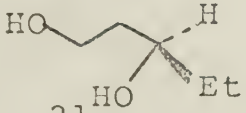
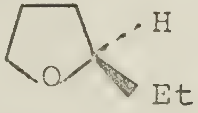
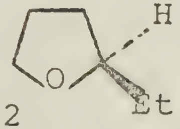
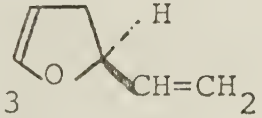
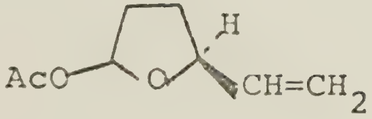
TABLE XIII

Absolute Configurations, Optical Purity and Sources of the Compounds Involved in the Conversion of 10 to 13.

Compound	Source	α_{λ}^{obs} (g/100 ml, 2-propanol)	$[\alpha]_{\lambda}^{t}$	Config.	Opt. purity (max. rotation predicted)
 10	Direct resolution	$\alpha_{365}^{24.1} = -0.465°$ (6.69)	-8.74°	R	6.67% (131°)
 18a	10	$\alpha_{D}^{24.6} = +0.053°$ (2.12)	+2.50°	S	6.67% (37.5°)
 18b	Direct resolution	$\alpha_{D}^{20} = 0.956°$ (7.04)	+13.60°	S	36.3%
 19	18b	$\alpha_{D}^{20} = -2.593°$ $= -0.175°$ (5.26)	$-2.593°^{\dagger}$ -3.320°	R	36.3% ($-7.13^{\dagger}$) known
 19	20	$\alpha_{D}^{22} = -0.077°$ (11.91)	-0.64°	R	6.99%

(continued...)

TABLE XIII (continued)

Compound	Source	α_{λ}^{obs} (g/100 ml 2-propanol)	$[\alpha]_{\lambda}^{t}$	Config.	Opt. purity (max rotation predicted)
 20	Direct resolution	$\alpha_{D}^{22} = -0.057°$†	-0.057°†	R	6.99% (0.815°†)
 21	20	$\alpha_{D(9.95)}^{22} = -0.111°$	-1.11°	R	6.99% (15.8°)
 22	21	$\alpha_{D(12.2)}^{22} = -0.099°$	-0.81°	R	6.99% (11.58°)
 22	13	$\alpha_{D(2.05)}^{25} = -0.025°$	-1.22°	R	10.52%
 13	23	$\alpha_{D(2.38)}^{25} = +0.096°$	+4.07	S	10.52% (38.68°)*
 23	Direct resolution	$\alpha_{D(2.00)}^{25} = +0.089°$	+4.45°	S	10.52% (42.30°)

† Neat in1dcm cell.

* Maximum rotation for 13 at 365 mμ is predicted to be 107.79°.

TABLE XIV

Observed Rotations at Different Wavelengths for Compounds Listed in Table XIII

Compound[a]	Observed rotation in (deg) 365 mμ	436 mμ	546 mμ	578 mμ	589 mμ
10	-0.744	-0.299	-0.102	-0.079	
18	3.509	2.095	1.155	1.001	0.956
19*	-4.950	-4.950	-3.041	-2.702	-2.594
19	-0.223	-0.150	-0.090	-0.080	-0.037
20*	-0.478	-0.207	-0.075	-0.062	-0.057
21	-0.252	-0.182	0.126	-0.117	-0.111
22	-0.458	-0.245	0.122	-0.105	-0.099
13	+0.269	+0.183	+0.112	+0.100	+0.096
23	+0.273	+0.176	+0.106	+0.093	+0.089

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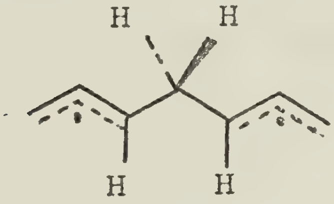
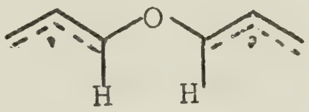
[a] All samples were examined in 2-propanol except those indicated by an asterisk which were neat in a 1 dcm cell.

DISCUSSION

The principle reason for carrying out this work has been to compare the racemization, and geometrical (*trans* to *cis*) isomerization of oxiranes with those of cyclopropanes. Quantum mechanical calculations by Hoffmann (18) and Hayes (34) indicate that the intermediate expected in these reactions should have greater diradical character in the trimethylene species 3 than in the oxatrimethylene species 15.



3



15

The non-bonded electron pair on the oxygen allows better conjugation than that of the pseudo p-orbital on the central methylene of 3. The implication from the quantum calculations are that the oxirane should racemize more readily than the analogous cyclopropane and that the oxirane should be slower to undergo geometrical isomerization. Operationally if the racemization is an electrocyclic process and only one mode of rotation to the intermediate, e.g. either con- or disrotation, is available then the rate constant for the geometrical isomerization will be infinitely smaller than the rate constant for the racemization. If however both con- and disrotatory modes are equally accessible then, invoking the principle of microscopic reversibility, we

we can state that the racemization rate constant will be twice that of the rate constant for the geometrical isomerization*. If only one chiral center of the optically active oxirane is rotated through 180° (the Smith mechanism) then the starting material is not racemized but is ultimately converted to **12**. This is summarized in Table XV.

TABLE XV

Operative Criteria

Path	Predicted k_3/k_1
Only one mode	0
Equivalent dis-and conrotation	2
Smith mechanism	∞

The ratios observed at 150.0°, for **10** and **2** are 0.014 and 1.34 (48). At 150° the oxirane racemizes 2.23 times faster than the cyclopropane, but the geometrical

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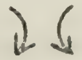
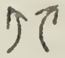
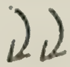
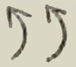
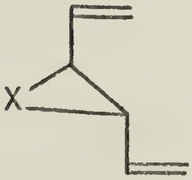
[*] A statistical factor of two is required here for while both ( and ) disrotations from an intermediate such as **15** give rise to the *cis* isomer, conrotation gives different enantiomers from each possibility ( and ).

isomerization is 0.0239 times slower for the oxirane than that of the cyclopropane. These results are summarized in Table XVI.

TABLE XVI

Comparison of Racemization and Geometrical Isomerization for

10 and 2 at 150°



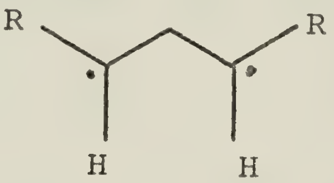
	Racemization	Geometrical isomerization
X = O	145	1.0
= CH_2	65	44

Mechanism of Oxirane Isomerization

The kinetic data indicate that the concerted electrocyclic process is favoured over the more random diradical process. A problem arises in just what one might expect of a diradical that is free to close to either *cis* or *trans*-2,3-divinyloxirane. If we are to use the definition of Hayes and Siu (34) then from the diradical we are equally likely to get ring closure to the *cis* isomer as to the *trans*. This does not take into account the relative thermodynamic stabilities of the *cis*- and *trans*- isomers. We shall first attempt to explain what we expect from a

diradical for the cyclopropanes and then the oxiranes.

If we assume that our diradical has a structure such as **24** where the alkyl groups R and R' are in the stable W-configuration and that it is free to close to either a *cis-* or *trans-* dialkylcyclopropanes, *sans orbital-symmetry factors*. It would seem reasonable that those factors which



24

control the relative thermodynamic stability of the ring closure products will be playing a role in the transition states leading to those products. If for example, R and R' are methyl then it is known that the *trans* isomer is more stable than the *cis* ($\Delta H° = -1.0$ kcal mole^{-1}) by a factor of 5.5 at 30° (4a). Thus if the magnitude of the steric effects were the same for the transition states as for the ground states we would have a reaction coordinate as in Figure 9 and $\delta\Delta G^{\ddagger} = \Delta H°$. This is likely to be too large an estimate and the effect will probably be somewhat attenuated. One possible indication of the attenuation is that the ring closure from triplet diradicals (49) gives a 1.55:1 ratio of *trans* to *cis-* 1,2-dimethylcyclopropane thus $\delta\Delta G^{\ddagger} = 0.26\ \Delta H°$. If instead of methyl we consider

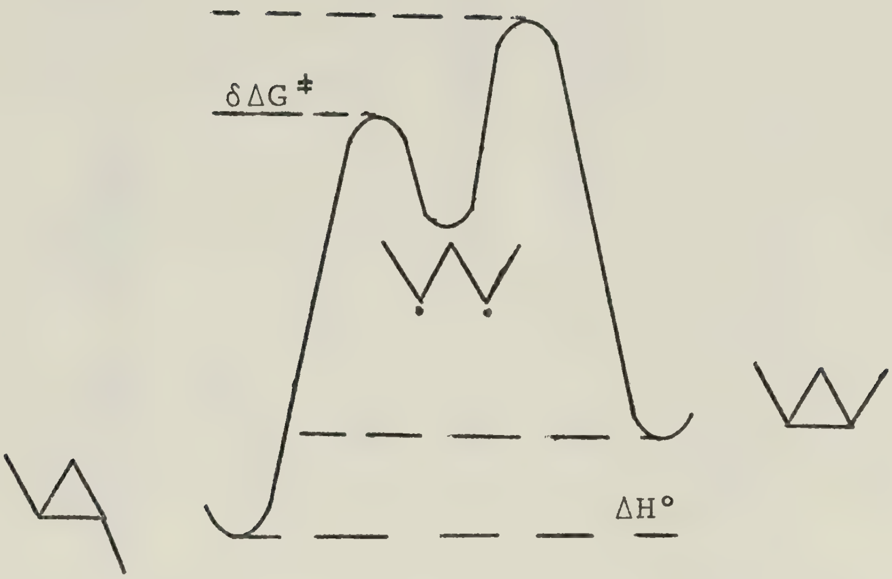


FIGURE 9. Assumed free energy profile for the ring closure of a trimethylene diradical.

the case of 1,2-diphenylcyclopropane we find that ΔH at 205° is 2.37 kcal mole^{-1}. Upon attenuating this value by 0.26 we find that for every mole of substrate going to a diradical that 0.66 moles will end up as racemic *trans* and 0.34 moles as *cis*-1,2-diphenylcyclopropane. This suggests that the analogous k_3/k_1 ratio for the diphenylcyclopropane is such that for any value greater than 1.04* the process is diradical and for any value less than this that we have some electrocyclic character. Crawford and Lynch (24)

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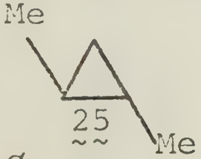
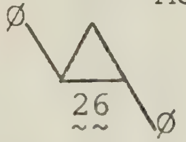
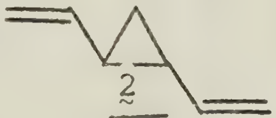
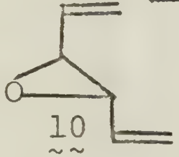
* This value is simply a ratio analogous to that in Table XV of 26 except that now we have incorporated some thermodynamic preference.

TABLE XVII

Operational Criteria for Diradical *versus* an Electrocyclic Process for Some 3-membered Ring Systems

Substrate	T	ΔH_T kcal mole^{-1}	$\delta\Delta G^{\ddagger}$ kcal mole^{-1}	k_3/k_1 no attenuation	(calc.) attenuated	k_3/k_1 observed	Mechanism
 25	30°	1.05	0.26	0.35	0.75[a]	-	-
 26	205°	2.37	0.62	0.17	1.04	4.7	diradical
 2	150°	1.7 est.	0.44	0.27	1.18	1.36	diradical
 10	150°	1.7 est.	0.44	0.27	1.18	0.014	electro-cyclic

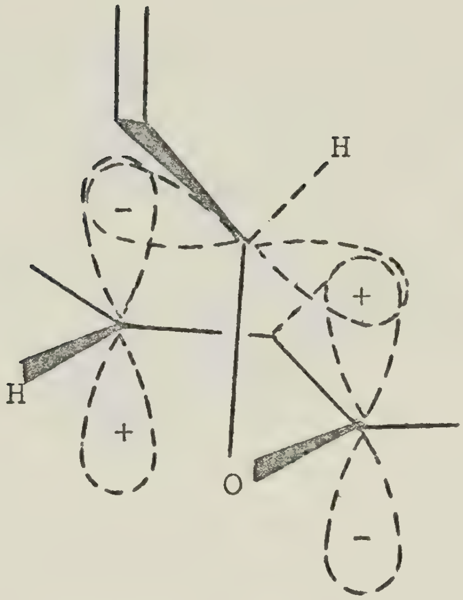
a. Value derived from ring closure of triplet species and used to calculate the attenuation factor.

observed a value of 4.7. The divinylcyclopropane may be expected to demonstrate steric effects intermediate between the methyl and phenyl, and thus assuming a value of $\Delta H° = 1.7$ kcal mole^{-1} we can get an analogous value for the k_3/k_1 ratio of 1.18 The value observed by Arai (48) for 1,2-divinylcyclopropane at 150° is 1.36, again implying that the isomerization has no electrocyclic component. Table XVII lists these values.

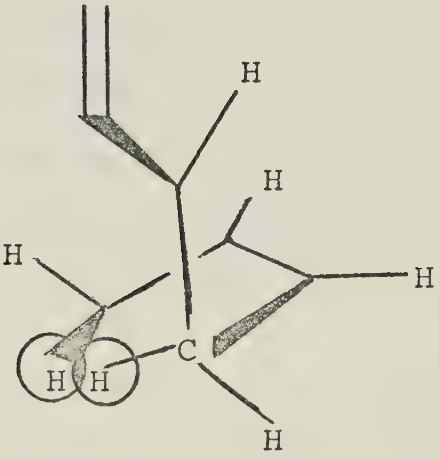
Lynch (50) has observed that *cis*- and *trans*- stilbene oxide (1,2-diphenyloxirane) have nearly the same equilibrium value as diphenylcyclopropane. Thus using the arguments for **10** that we used for **2** we would expect a value of $k_3/k_1 = 1.18$ or greater for a diradical process and that an electrocyclic process would give a smaller ratio. The observed value 0.014 indicates less than 1% diradical character.

Mechanism of the 1,3-Sigmatropic Rearrangement

During the racemization of R-(-)-**10** the formation of R-(-)-**13** was observed in the infinity tubes. By relating both **10** and **13** to 3-hexanol we can see that the 1,3-sigmatropic shift must have occurred with inversion of configuration at the migrating center. This process can be classified as a ${}_{\sigma}2_{a} + {}_{\pi}2_{s}$ electrocyclic reaction (51). The transition state for this process may be visualized as approximating



A frequent point of conjecture has been as to why the thermal isomerization of *trans*-1,2-divinylcyclopropane **2** does not give rise to 4-vinylcyclopentene. We suggest that the replacement of the oxygen in **10** by a methylene group would give rise to serious steric interactions from the hydrogens of the cyclopropane methylene group and that terminal hydrogen of the allylic frame work that is *trans* to the methine hydrogen.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EXPERIMENTAL

All boiling points are uncorrected.

The infrared spectra were obtained on a Perkin-Elmer Model 421 spectrophotometer. The nuclear magnetic resonance spectra were obtained on a Varian A-60 spectrometer. Rotations were measured on a Perkin-Elmer Polarimeter Model 141.

Constant temperature in the air bath used for the kinetics was controlled by Melabs proportional temperature controller model CTC-1A and measured by Melabs temperature bridge Model CTB-1.

Synthesis

Zinc-copper couple. An aqueous solution containing cupric sulphate pentahydrate (20 g) was added dropwise to a rapidly stirred mixture of zinc dust (200 g) dispersed in ice (300 g) and water (300 ml). After addition, stirring was continued for 30 minutes. The couple was filtered and washed several times with tetrahydrofuran, dried over phosphorus pentoxide under vacuum at 50° and stored in a vacuum desiccator.

meso and *rac*-1,5-Hexadien-3,4-diol (**16**). Acetic acid (92.4 g, 1.54 mol) was added over a period of one hour to a zinc-copper couple (220 g) and acrolein (84 g, 1.50 mol) in dry tetrahydrofuran (350 ml). During the addition the

reaction mixture was stirred under a nitrogen atmosphere and the temperature maintained at -10°. After the addition the mixture was allowed to slowly warm to room temperature and then was stirred for another 18 hours. The solution was decanted from the dark grey residue, which was then washed several times with fresh tetrahydrofuran. The washings were combined and dried over anhydrous potassium carbonate. The drying agent was filtered off, tetrahydrofuran was removed on a rotatory evaporator, and the product was purified by distillation under vacuum, to give a mixture of *meso* and *rac*-1,5-hexadien-3,4-diol (60 g, 70%); bp 87-98°/13 mm, (lit. 97-98°/13 mm). Signals were observed in the nmr spectrum in $CDCl_3$: τ 3.8-4.9 multiplet, τ 5.78 poorly resolved doublet, τ 6.00 poorly resolved doublet, τ 6.75 sharp singlet. The integration gave the ratio of 6:1:1:2 (52).

Divinylethylene carbonate (16a) was prepared according to the procedure of Braun (35). A mixture of 16 (57 g, 0.6 mol), diethylcarbonate (71 g, 0.6 mol) and anhydrous potassium carbonate (0.2 g) was slowly heated to 110°. At this temperature the reaction started and ethyl alcohol was fractionated off *via* a Vigreux column. After the theoretical amount of ethyl alcohol was removed, the residue was fractionated, yielding the mixture of *cis* and *trans*-16a (51.8 g, 74%); bp 63-68°/0.2 mm (lit. 64°/0.2 mm).

Note: This reaction is very sensitive to moisture and appears to have an induction period.

trans-2,3-Divinyloxirane (10) and 4,5-Dihydrooxepine (12). A mixture of 16a (140 g, 1.47 mol) and lithium chloride powder (5 g) was heated slowly to 200-220° and the distillate collected in a dry-ice cooled receiver. The distillate was washed with cold water and dried over anhydrous magnesium sulphate. Distillation of the crude product, through a spinning-band column, afforded a constant boiling fraction (25 g, 25%); bp 105°/700 mm (lit. 108°/760mm). Gas chromatographic (gc) analysis showed two components with relative peak areas of three to one. They were separated on a preparative gc, using a 10 ft column (15% ββ'-oxidipropionitrile on firebrick). First fraction (retention time 15 min., column temperature 70°, flow rate 60 ml/min was 12 and second fraction (retention time 20 min) was 10. Ir and nmr shown on Figures 4 and 3 were identical with those previously published (35).

3-Chloro-4-acetoxy-1,5-hexadiene (17), was prepared by the method of Stogryn (36). To a stirred suspension of 16 (114 g, 1.0 mol) and calcium chloride (20.8 g, 0.19 mol) was added acetyl chloride (95 g, 1.22 mol) over a period of 45 minutes. During the addition the temperature was maintained below 10°, and the mixture kept under an atmosphere of nitrogen. The reaction mixture was stirred for an additional

40 hours at room temperature and then heated for one hour at 50°, poured onto ice, neutralized with cold aqueous sodium bicarbonate and finally extracted several times with ether. The ether extracts were combined and dried over anhydrous potassium carbonate. The drying agent was filtered off and the ether was removed by simple distillation. The residue was distilled through a spinning-band column, yielding **17** (73.2 g, 50%); bp 90-95/20 mm. (lit. 88-93°/19 mm)

cis- and *trans*-2,3-Divinyloxirane (**11** and **10**). In a three litre three-necked flask, equipped with a mechanicl stirrer, dropping funnel and dry-ice cooled receiver, there was placed sodium hydroxide (130 g, 3.2 mol), potassium hydroxide (130 g, 2.3 mol) water (13 g) and ethylene glycol (250 ml). **17** (92 g, 0.62 mol) was added dropwise while the temperature was maintained at 40-50° and the pressure at 10-15 mm. The product, as a mixture with water, was collected in a dry-ice cooled receiver. The layers were separated and aqueous layer extracted several times with ether. The extracts were combined and dried over anhydrous potassium carbonate. The drying agent was filtered off and the ether was removed by distillation through a Vigreux column. The mixture of **10** and **11** was heated at 100° to ensure conversion of **11** to **12** and distilled to yield **10** and **12** (26 g, 54%) (36).

Di-3-pinanylborane , was prepared by the method of Brown (37). In a 50 ml three-necked flask, equipped with

condenser, dropping funnel and a rubber septum, to permit removal of a sample, there was placed (+)-α-pinene (5.44 g, 0.04 mol, $[\alpha]_D$ = 48.7°), sodium borohydride (0.57 g, 0.015 mol) and 12 ml of diglyme, which had been distilled *in vacuo* from lithium aluminum hydride. The flask was immersed in an ice bath and kept under a nitrogen atmosphere. Diborane was generated by adding freshly distilled boron trifluoride etherate, (2.84 g, 0.02 mol) (distilled *in vacuo* from calcium hydride). Stirring and cooling was continued for four hours, and di-3-pinanylborane precipitated from the solution.

Resolution of **10**. A mixture of **10** (5.10 g, 0.02 mol) and diglyme (5 ml), which had been distilled *in vacuo* from lithium aluminum hydride, was placed in a 50 ml three-necked flask, equipped with a condenser, magnetic stirrer and a rubber septum on one neck. The mixture was stirred, cooled to -20° and kept under an atmosphere of nitrogen. Di-3-pinanylborane (0.02 mol) in diglyme, was introduced in a dropwise manner with the aid of a syringe, through the rubber septum. After the addition the mixture was kept for one hour at -20°, and then allowed to warm gradually over a period of three hours, to 0°. Finally it was kept for two hours in an ice bath. Then 5 ml of water was added to destroy the excess sodium borohydride and the mixture distilled from 0-30°/10 mm and the distillate collected into a dry-ice receiver. The distillate was a mixture of

unreacted **10**, some (+)-α-pinene, water and some diglyme. The layers were separated and upper layer was dried over anhydrous sodium sulphate. Compound **10** was isolated by preparative gc (10 ft column, 15% β,β'-oxidopropionitrile on firebrick, at 60°). Gc analysis showed presence of about one percent of **12** as the only impurity. Ir and nmr spectra were identical with the racemic **10**. The recovered **10** (2.0 g, 78.5%) was optically active (see Table V).

*1,5-Hexadiene-3-ol (**18**).* To dry magnesium turnings (30.5 g, 1.0 mol) there was added anhydrous ether (300 ml), a crystal of iodine and allyl bromide (5 g). The allyl bromide had been shaken with phosphorus pentoxide and distilled immediately before using. The reaction was started by careful warming and when the refluxing slowed down, allyl bromide (75 g, 0.5 mol) in anhydrous ether (1800 ml) was added dropwise, at such a rate that steady refluxing was maintained for 4-5 hours. The reaction mixture was kept under an atmosphere of nitrogen. After the addition the flask was immersed in a water bath and the reaction mixture gently refluxed for 30 minutes. The acrolein (20.6 g, 0.28 mol) was then added over a period of 30 minutes. Stirring was continued for an additional 15 minutes and the mixture allowed to stand overnight. Next day, the mixture was decomposed with ice and just enough dilute sulphuric acid to dissolve the sludge. The aqueous layer was extracted

several times with ether. Ether washings were combined and dried over anhydrous potassium carbonate. The drying agent was removed by filtration and the volatile products and ether were distilled off. Distillation of the residue yielded **18** (19.37 g, 75% based on acrolein); bp 128-132°/700 mm or 49°/21 mm (lit. 125-135°/760 mm). The nmr spectrum in $CDCl_3$ showed signals at τ 3.8 - 5.1 multiplet, τ 5.84 quartet, τ 7.7 triplet and τ 8.13 sharp singlet. The integration of the spectrum gave the ratio of 6:1:2:1 (42).

1,5-Hexadien-3-yl hydrogen phthalate. In a 300 ml round bottomed flask, equipped with a condenser and a drying tube, were placed **18** (27 g, 0.276 mol), phthalic anhydride (41 g, 0.276 mol) and dry pyridine (54 ml). The mixture was kept for one hour on a steam-bath and then allowed to stand overnight at room temperature. Next day the flask was immersed in an ice water bath, ether and water were added, followed by concentrated hydrochloric acid (75 ml). The solution was extracted several times with ether, the ether extracts were combined, washed with water and dried over anhydrous sodium sulphate. The drying agent was filtered off and the ether was removed on a rotatory evaporator. The remaining syrup was poured into a solution of sodium carbonate (43 g) in water (289 ml). This solution was allowed to stand one hour at room temperature and was then extracted with ether. The aqueous layer was cooled and acidified with concent-

rated hydrochloric acid (62.5 ml) and extracted several times with chloroform. The organic layer was dried over anhydrous sodium sulphate. The drying agent was filtered off and the chloroform was removed on a rotatory evaporator. The product consisted of a sticky syrup (50 g, 74%). Ir in chloroform showed the following infrared maxima: 3.10-3.60 (broad), 5.80 (s), 5.88 (s), 6.10 (w), 10.10 (m), 10.90 (m), 13.80 (w), (43).

Resolution of 1,5-hexadien-3-yl-hydrogen phthalate. 1,5-Hexadiene-3-hydrogen phthalate (31 g, 0.126 mol) was dissolved in dry acetone (79 ml), which had been distilled from phosphorus pentoxide. The solution was heated until boiling and brucine (38 g, 0.096 mol) was added. The hot solution was filtered and slow crystallization was allowed to occur at room temperature, and then placed in a refrigerator. After a few hours the brucine salt crystallized out. Upon four recrystallizations from acetone it was decomposed with dilute hydrochloric acid and (+)-1,5-hexadiene-3-yl hydrogen phthalate extracted with ether. After removal of the ether, the ester was dissolved in a 3M sodium hydroxide and (+)-**18** was steam-distilled. The steam-distillate was extracted several times with ether, the ether extracts were combined and dried over anhydrous potassium carbonate. The drying agent was filtered off and the ether removed by distillation through a Vigreux column.

The product (+)-**18** (4 g, 29.6%); bp 130-132/700 mm (lit. 133-134°/atm. press.) was optically active (see Table XIII), (43).

*Reduction of (-)-**10**.* Lithium aluminum hydride (0.114 g, 0.003 mol) was dissolved in a dry ether (6 ml) and stirred under an atmosphere of nitrogen. Compound (-)-**10** (0.300 g, 0.003 mol) in dry ether (2 ml) was added dropwise (specific rotation of (-)-**10** used, is shown in Table XIII). After the addition the mixture was stirred at room temperature for an additional three hours. The excess of hydride was decomposed by adding wet ether at 0°. The aluminate complex was decomposed by the addition of 3M sodium hydroxide at 0°, and the solution extracted several times with ether. The ether layer was dried over anhydrous sodium sulphate. The drying agent was filtered off and most of the ether distilled through a spinning-band column. Preparative gc was used to isolate (+)-**18** (85% Carbowax on chromosorb, at 70°). Its ir and nmr were identical with the original sample. (For specific rotation see Table XIII).

*Hydrogenation of (+)-**18** to (-)-**19**.* In a 300 ml three-necked flask equipped with condenser, dropping funnel and drying tube, were placed (+)-**18** (2.7 g, 0.027 mol), sodium azodicarboxylate (17.8 g, 0.137 mol) in methanol (220 ml). The suspension was stirred and acetic acid (13.2 g, 0.22 mol)

in methanol (137 ml) was added dropwise. After the addition the reaction mixture was stirred for 30 minutes and water was carefully added until the yellow color disappeared. The mixture was extracted several times with pentane. (The rest of the alcohol can be recovered by continuous extraction by ether). Pentane extracts were combined and dried over anhydrous magnesium sulphate. The drying agent was filtered off and the pentane was removed by distillation through a Vigreux column. The product was purified by short-path distillation *in vacuo*. Nmr, ir and gc retention times were identical with those of authentic 3-hexanol. (For specific rotation see Table XIII), (53).

1-Hexen-4-ol (**20**) was prepared by the procedure of Gaudemar (44). A 500 ml round bottom flask, equipped with mechanical stirrer, dropping funnel, condenser and inlet for nitrogen, was charged with activated zinc*. A solution of dry allyl bromide (30g, 0.25 mol) in dry tetrahydrofuran (125 ml) was prepared and 20 ml of this solution was added to the reaction flask. The reaction started spontaneously. The

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* 30-Mesh zinc had been treated with hot concentrated sulphuric acid and a few drops of nitric acid for 10 minutes. The solution was decanted and zinc washed with water, filtered off and dried.

reaction flask was immersed in a cold water bath and the temperature was kept at 10° during the addition of the remainder of the allyl bromide solution which was added dropwise over a period of two hours. Propionaldehyde (14.5 g, 0.25 mol) was then introduced dropwise at room temperature and the reaction mixture stirred for an additional hour. Dilute hydrochloric acid and ice were added and the solution was continuously extracted with ether. The organic layer was dried over anhydrous potassium carbonate. The drying agent was removed and the ether and tetrahydrofuran were distilled off through a Vigreux column. Compound **20** (16 g, 64% based on propionaldehyde) was purified by distillation; bp 129-132°/atm. press. (lit. 130-2°/760mm). The nmr spectrum in $CDCl_3$ displayed signals at τ 3.78-5.1 multiplet, τ 6.2 quintet, τ 7.8 multiplet, τ 8.1 sharp singlet, τ 8.25-8.85 multiplet, τ 9.1 triplet, in the integration ratio of 3:1:2:1:2:3.

Resolution of ***20****.* It was carried out, following the same procedure as outlined for **18**.

*Hydrogenation of (+)-**20** to (-)-**19**.* It was carried out, following the same procedure for the hydrogenation of (+)-**18** to (-)-**19**. Reduced product (-)-**20** was identified by its nmr and ir spectra and its gc retention time.

*(-)-1,4-Hexanediol (**21**)* was prepared from (-)-**20** by the

general procedure of Brown for the hydration of double bond by the hydroboration reaction (45). Borane in tetrahydrofuran (23 ml, 1.34 M) at 0°, was added in a dropwise manner to (-)-**20** in dry tetrahydrofuran (45 ml). After the addition, the mixture was stirred for 30 minutes at room temperature, and the excess borane was decomposed by careful addition of wet tetrahydrofuran at 0°. Sodium hydroxide (45 ml, 3 M) was then added, followed by the dropwise addition of hydrogen peroxide (15 ml, 30%) and the temperature was maintained at 30-50° throughout this addition. Stirring was continued for one hour at room temperature. Solid potassium carbonate (40 g) was added, the tetrahydrofuran layer separated and the aqueous phase was extracted twice with fresh tetrahydrofuran. The extracts were combined and dried over anhydrous magnesium sulphate. The drying agent was removed and tetrahydrofuran distilled off. Product (-)- **21** (3.2 g, 90%); bp 128-131°/16 mm (lit. bp 134-5°/18.5 mm) (54) was purified by distillation. Gc analysis showed the presence of about 3% of 2,4-hexanediol. The nmr spectrum in D_2O showed signals at τ 6.35 illresolved multiplet, τ 8.2-8.9 broad multiplet, τ 9.1 triplet, in the integration ratio of 3:5.7:2.8.

(-)-2-Ethyltetrahydrofuran (**22**), was prepared by the procedure of Coates (46). p-Toluenesulfonyl chloride (5.16 g, 0.027 mol) was slowly added at 0°, to a solution of

(-)-**21** (3 g, 0.025 mol) in a dry pyridine (36.4 ml). The reaction mixture was stirred at room temperature until gc analysis showed the absence of the starting material. A new peak with shorter retention time appeared. Cold water was added and the reaction mixture extracted six times with pentane. Pentane extracts were combined and washed with cold 2N hydrochloric acid and dried over anhydrous magnesium sulphate. The pentane was removed by distillation through a spinning-band column and the residue purified by short path distillation. Product (-)-**22** (0.97 g, 30%) was more than 99% pure by gc analysis. Reported bp 108°/758 mm (55). The nmr spectrum in $CDCl_3$ displayed peaks at τ 6.0-6.5 broad multiplet, τ 7.85 - 8.70 broad multiplet, τ 9.1 triplet in the integration ratio of 1:2:1.

Kinetic studies. In a typical run, a sample of optically active **10** (about 1 mmol) was weighed and degassed on a vaccum line. It was distilled, under vacuum, into a break-seal tube of 30 ml capacity, cooled by liquid nitrogen. The tube was sealed off and removed from the vacuum line and heated in a constant temperature air-bath.

At the prescribed time the break-seal was pulled out of the bath and immersed in an ice-water bath to quench the reaction. It was sealed on the vacuum line and after the vacuum of about 10 microns was achieved the break-seal was opened and the content was distilled into a weighed 1 ml

volumetric flask attached to the vacuum line and cooled by liquid nitrogen. The content of the volumetric flask was allowed to come to room temperature and the flask removed from the vacuum line and weighed. 2-Propanol was added up to a volume of 1 ml and the weight of the solution was accurately measured. Concentrations of **10** in 2-propanol were calculated in percentage to avoid volumetric error by small volume.

The solution was then transferred into a polarimetric tube (1 ml volume, 1 dcm long) and the rotation was measured at constant temperature. Zero point of the instrument was taken before each measurement with the pure solvent at the same temperature and the correction applied. Precision of the measurement was ± 0.002°. All samples were analyzed by gc, after the measurement of the rotation was carried out. Table XVII shows the experimental data obtained for the racemization of **10** at 150°.

TABLE XVIII

Experimental Data for the Racemization of 10 at 150.05 ± 0.03°

Sample no	Time (secx10^3)	Weight of 10 (gr)	Weight of 10 + 2-propanol	%	α_{365}^{obs} (deg)
0	0	0.0875	0.7781	10.37	-0.588*
1	3.6	0.0795	0.7642	10.40	-0.521
2	7.2	0.0771	0.7600	10.15	-0.430
3	10.8	0.0807	0.7576	10.12	-0.354
4	17.88	0.0773	0.7637	10.13	-0.271
5	25.2	0.0778	0.7715	10.08	-0.185
6	infinity	0.0818	0.7789	10.50	-0.060

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* Optical purity of 10 used for kinetic measurements, was 5.56%.

REFERENCES

1. H. M. Frey, Advan. Phys. Org. Chem., 4, 147 (1966).

2. T. S.Chambers and G. B. Kistiakowsky, J. Am. Chem. Soc., 56, 399 (1934).

3. (a) B.S. Rabinovitch, E.W.Schlag and K. B. Wiberg, J. Chem. Phys., 28, 504 (1958).

   (b) E. W. Schlag and B.S. Rabinovitch, J. Am. Chem. Soc., 82, 5996 (1960).

   (c) B. S. Rabinovitch, D. W. Setser, and F. W. Schneider, Can. J. Chem., 39, 2609 (1961).

   (d) D. W.Setser and B. S. Rabinovitch, J. Am. Chem. Soc., 86, 564 (1964).

4. (a) M. C. Flowers and H. M. Frey, Proc. Roy. Soc., (London) A257, 122 (1960).

   (b) M. C. Flowers and H. M. Frey, J. Chem. Soc., 2758 (1960).

5. (a) H. E. O'Neal and S. W. Benson, J. Phys. Chem., 72, 1866 (1968).

   (b) W. B. De More and S. W. Benson, Advan. Photochem., 2, 219 (1964).

   (c) S. W. Benson, J. Chem. Phys., 34, 521 (1961).

6. F. T. Smith, ibid., 29, 235 (1958).

7. J. Hine, J. Org. Chem., 31, 1236 (1966).

8. C. G. Overberger and A. E. Borchert, J. Am. Chem. Soc., 82, 1007 (1960).

9. (a) R. J. Ellis and H. M. Frey, J. Chem. Soc., 959 (1964).
   (b) K. W. Eger, D. M. Golden, and S. W. Benson, J. Am. Chem. Soc., 86, 5420 (1964).

10. R. J. Ellis and H. M. Frey, J. Chem. Soc. Phys., Sect. 553 (1966).

11. M. Robert Willcott, Virgil H. Cargle, J. Am. Chem. Soc., 89, 723 (1967).

12. M. Robert Willcott, Virgil H. Cargle, J. Am. Chem. Soc., 91, 4310 (1969).

13. M. C. Flowers and H. M. Frey, J. Chem. Soc., 3547 (1961).

14. C. A. Wellington, J. Phys. Chem., 66, 1671 (1962).

15. R. J. Ellis and H. M. Frey, J. Chem. Soc., 5578 (1964).

16. W. von E. Doering, B. M. Ferrier, E. T. Fossel, Jr., G. Klumpp, R. M. Rubin and M. Saunders, Tetrahedron 23, 3943 (1968).

17. (a) E. Vogel, Angew. Chem., 72, 4 (1960).
    (b) E. Vogel, K.-H. Ott, and K. Gaiek, Ann. 644, 172 (1961).

18. R. Hoffman, J. Am. Chem. Soc., 90, 1475 (1968).

19. R. B. Woodward and R. Hoffmann, J. Am. Chem. Soc., 87, 395, 2511 (1965).

20. R. J. Crawford and A. Mishra, J. Am. Chem. Soc., 87, 3768 (1965).

21. B. M. Trost, W. L. Schinski, and I. B. Mantz, J. Am. Chem. Soc., 91, 4321 (1969).

22. J. P. Freeman, D. G. Pucci, and G. Binsch (private communication).

23. J. A. Berson, J. M. Balquist, J. Am. Chem. Soc., 90, 7343 (1968).

24. R. J. Crawford and T. R. Lynch, Can. J. Chem., 46, 1457 (1968).

25. R. G. Bergman, W. L. Carter, J. Am. Chem. Soc., 91, 7411 (1969).

26. C. S.Elliot and H. M. Frey, J. Chem. Soc., 900 (1964).

27. K. H. Mueller and V. D. Walters, J. Am. Chem. Soc., 73, 1458 (1951).

28. T. J. Hardwick, Can. J. Chem., 46, 2454 (1968).

29. M. C. Flowers, R. M. Parker and M. A. Voisey, J. Chem. Soc., (B), 234 (1970).

30. E. Vogel and H. Günter, Ang. Chem. internat. Edit. 6, 385 (1967).

31. J. C. Pommelet, N. Manisse et J. Chuche, C. R. Acad. Sc. Paris, t.270 (1970).

32. L. A. Paquette, L. M. Leichter, J. Am. Chem. Soc., 92, 1765 (1970).

33. W. J. Linn and R. E. Benson, J. Am. Chem. Soc., 87, 3657 (1965).

34. E. F. Hayes and A. K. Q. Siu (private communication).

35. R. A. Braun, J. Org. Chem., 28, 1383 (1963).

36. E. L. Stogryn, M. H. Gianni and A. J. Passannante, J. Org. Chem., 29, 1275 (1964).

37. H. C. Brown and G. Zweifel, J. Am. Chem. Soc., 83, 486 (1961).

38. H. C. Brown and W. Korytnyk, J. Am. Chem. Soc., 82, 3866 (1960).

39. L. P. Hammet, "Introduction to Physical Chemistry", McGraw Hill Book Co., New York, 1960, pp.91-94.

40. H. C. Brown, N. R. Ayyangar and G. Zweifel, J. Am. Chem. Soc., 86, 397 (1964).

41. J. Kenyon and R. Poplett, J. Chem. Soc., 273 (1945).

42. L. W. Butz, E. W. J. Butz and A. M. Gaddis, J. Org. Chem., 5, 171 (1940).

43. Levene and Haller, J. Biol. Chem., 83, 185 (1929).

44. M. Gaudemar, Bull. Soc. Chim. France 974 (1962) N° 175.

45. H. C. Brown, Org. React. Vol. 13, p.32.

46. R. M. Coates and L. S. Melvin Jr., J. Org. Chem., 35, 865 (1970).

47. C. Glacet, C. A., 43, 4253i (1949).

48. Report of M. Arai to R. J. Crawford, 1969.

49. R. Moore, A. Mishra and R. G. Crawford, Can. J. Chem., 46, 3305 (1968).

50. Report of T. R. Lynch to R. J. Crawford, 1969.

51. R. B. Woodward and R. Hoffmann, "The Conservation of Orbital Symmetry" Verlag Chemie GmbH 1970, pp.114-120.

52. R. A. Braun, C. A. 64, 15743e (1966).

53. W. C. Baird Jr., B. Franzus, and J. H. Surridge, J. Am. Chem. Soc., 89, 410 (1967).

54. C. Glacet, Compt. Rend. 218, 283 (1944).

55. R. Paul, Bull. Soc. Chim. France (5), 5, 1053 (1938).

56. A. N. Frost and R. L. Pearson, "Kinetic and Mechanism", John Wiley and Sons, Inc., New YOrk, 1961, 2nd edition, pp. 99-100.

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